Search for LFV and Light New Physics at Belle II

Youngjoon Kwon (Yonsei Univ.)

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Overview

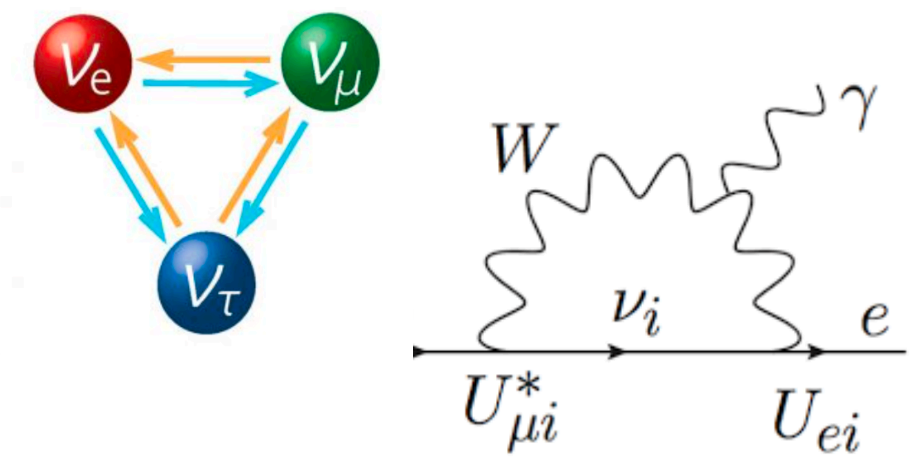
- Introduction
  - general physics motivation
  - Belle II
- Recent results
  - for LFV (and BNV)
  - for light new physics
- Closing

(C)LFV = (charged) lepton flavor violation

BNV = baryon number violation

Motivation

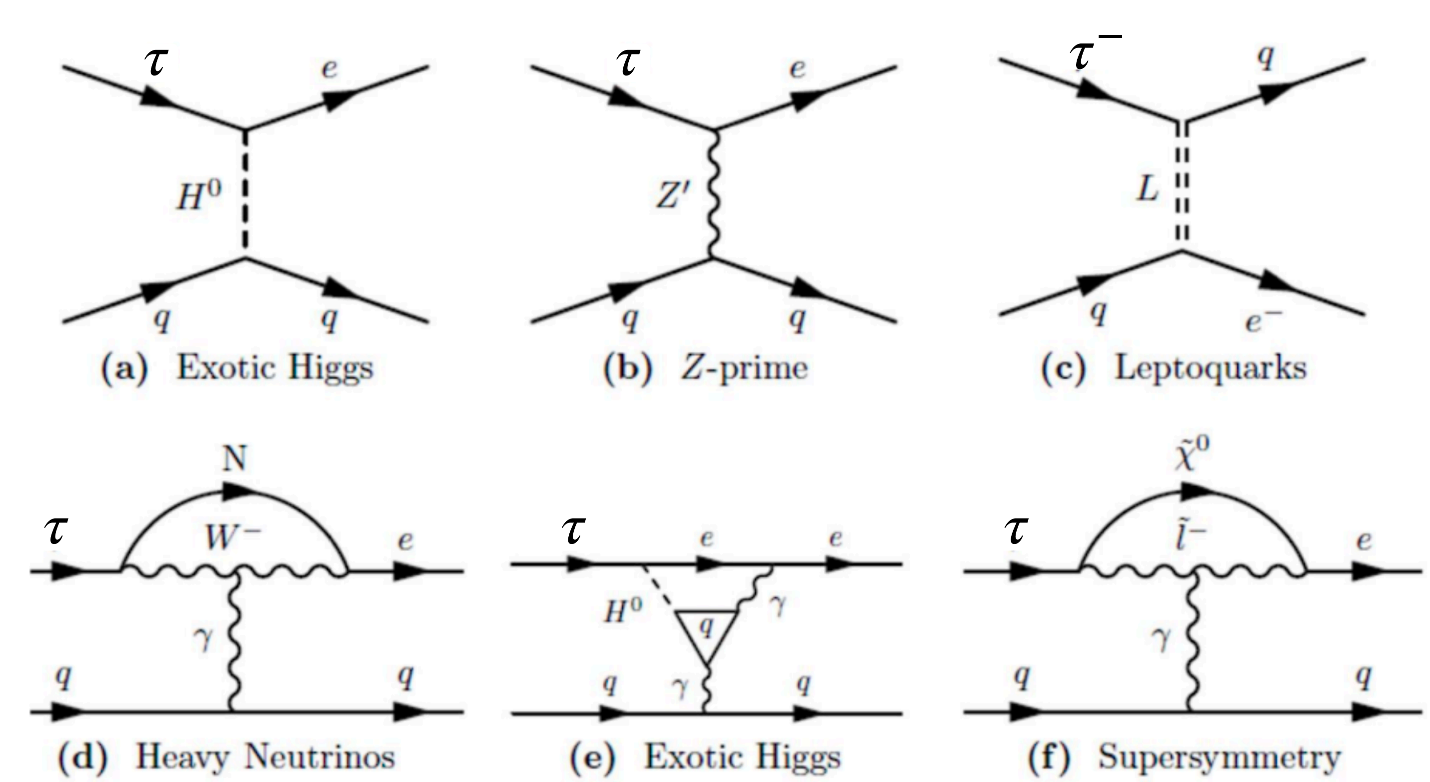
- lepton number, lepton flavor, baryon number
  - each, conserved in the SM (with $m_\nu = 0$ for LF) due to accidental symmetries
  - with $m_\nu \neq 0$, LFV can occur but suppressed by $(m_\nu/m_W)^4$



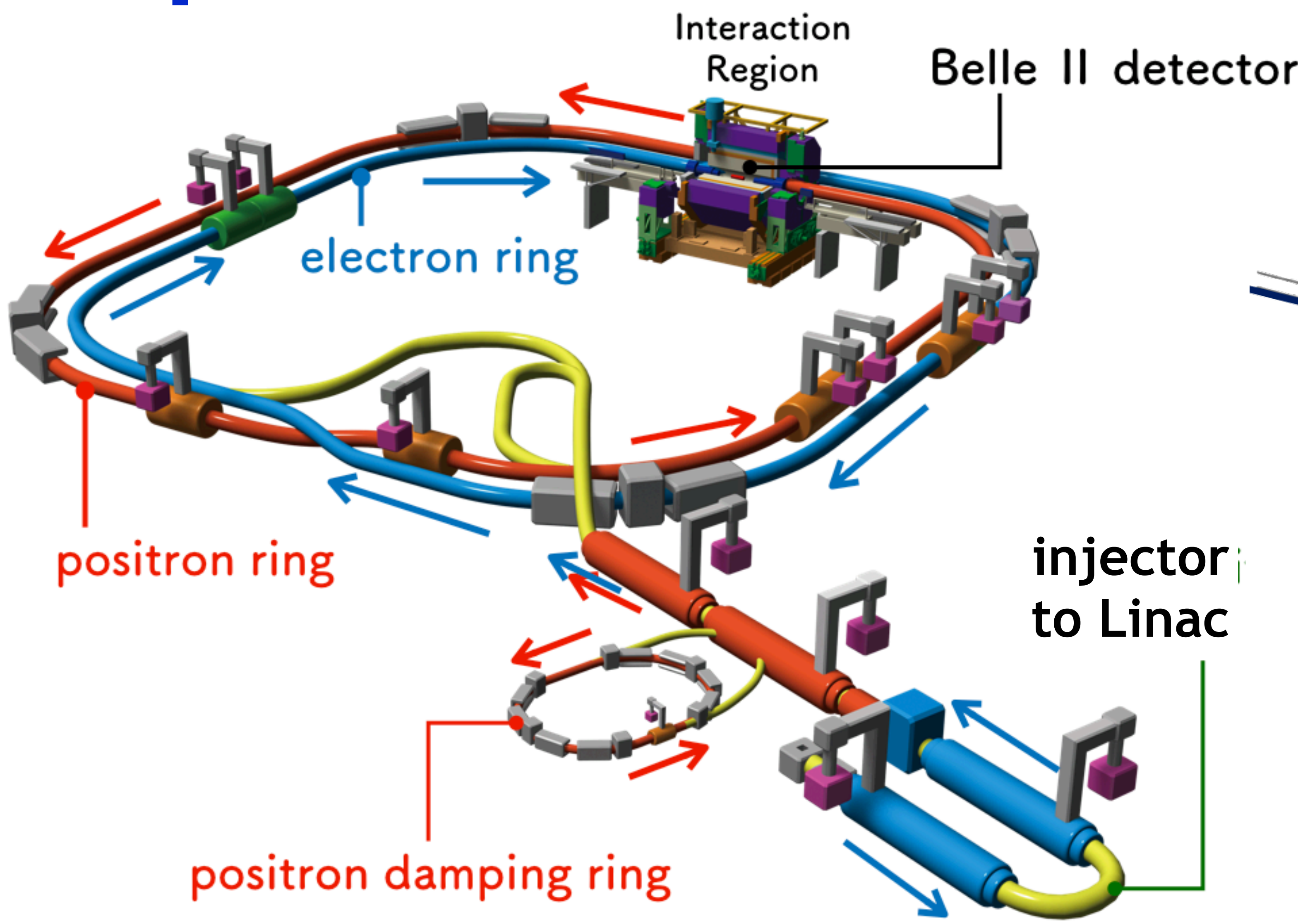
$$\mathcal{B}(\tau \to l\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\tau i} U_{\mu i} \frac{\triangle^2_{3i}}{m_W^2} \right|^2 \leq 10^{-53} \sim 10^{-49}$$

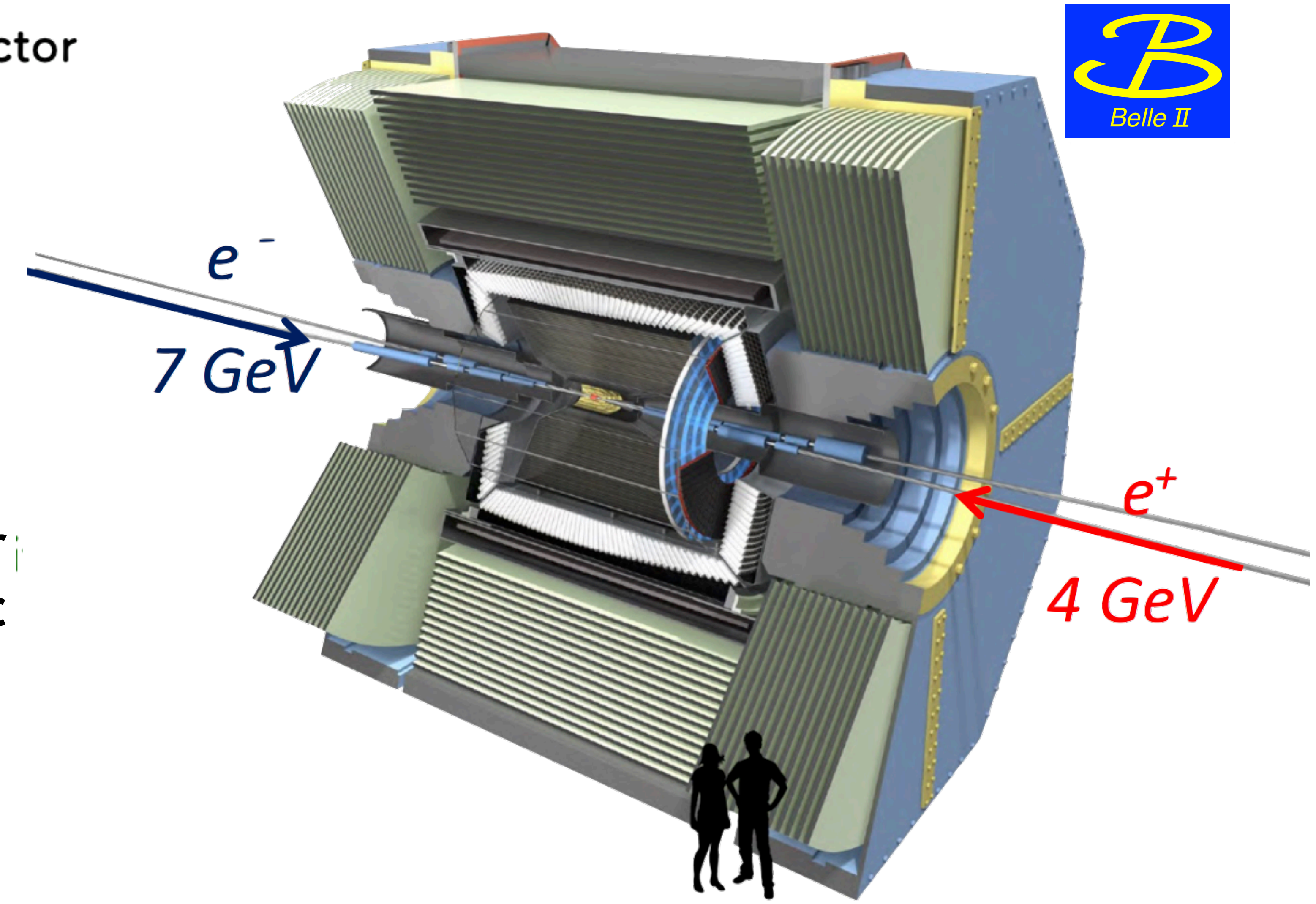
- Observation of LFV will be a clear signal of NP
  - many BSM scenarios predict CLFV with $\mathcal{B}_{\rm CLFV} \sim (10^{-10} - 10^{-7})$

- BNV
  - crucial ingredient for BAO (matter-antimatter asymmetry)



SuperKEKB and Belle II





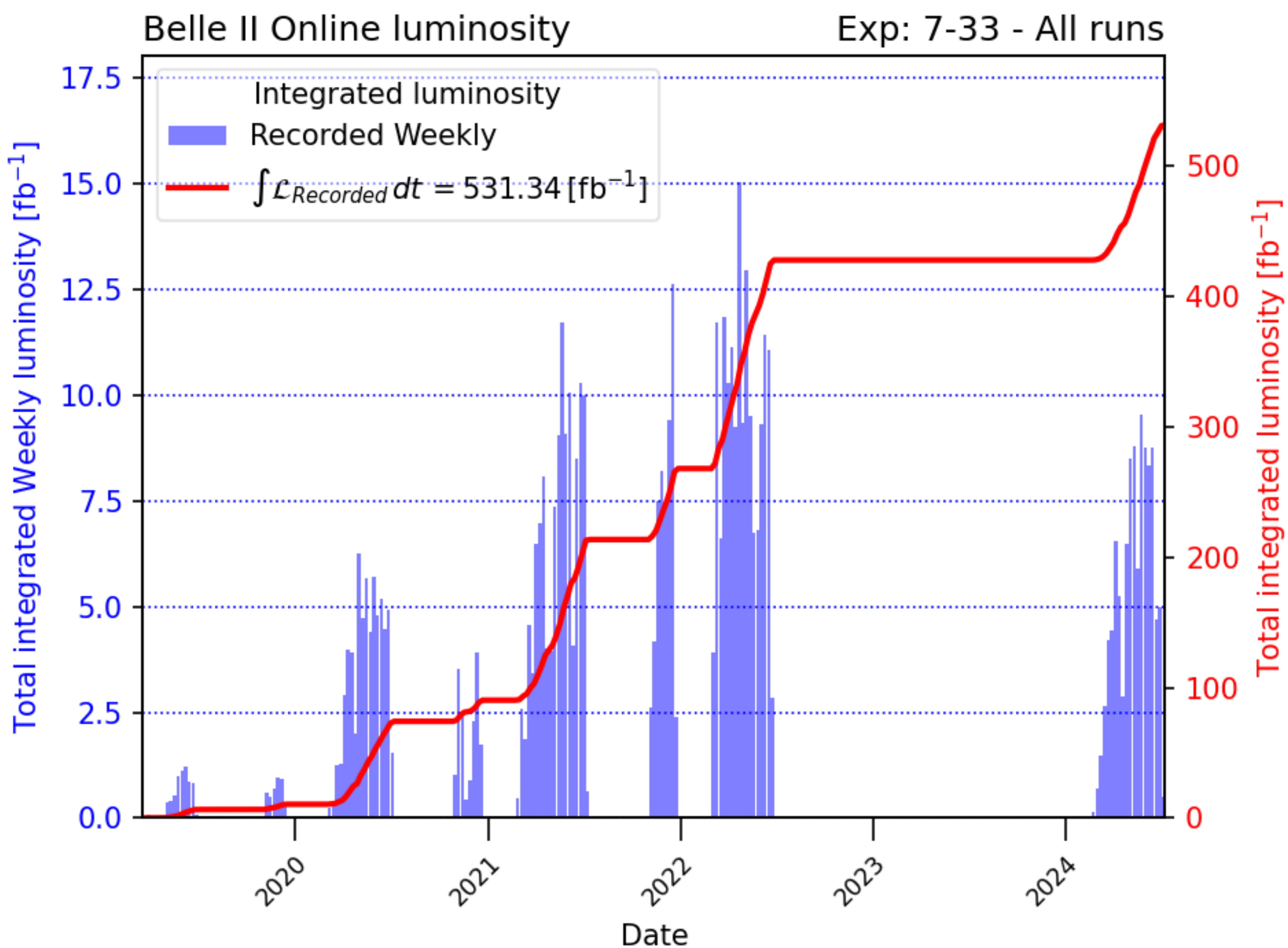
$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

$$\sqrt{s} = 10.58\ \text{GeV} = m_{\Upsilon(4S)}c^2$$

We also have data taken off-resonance as well as energy scan around $\Upsilon(5S)$

- Not just a “B-factory”, but tau-factory as well (charm-factory, too)
  $\sigma(e^+e^- \to \Upsilon(4S) \to B\overline{B}) \sim \sigma(e^+e^- \to \tau^+\tau^-) \sim O(1\ \text{nb})$
- τ-tagging ➔ make most τ LFV analyses nearly background-free

Belle II luminosity



Belle (1999-2010) Luminosity

$$\int \mathscr{L}_{\rm total} = 1039\ \rm fb^{-1}$$

- $980\ \rm fb^{-1}$ for $\tau^+\tau^-$
- $25\ \rm fb^{-1}$ at $\Upsilon(2S)$

For LFV (and BNV)

$$\tau^+ \to \mu^+ \mu^- \mu^+$$

Belle II

$$\tau^+ \to \ell^+ V^0$$

BELLE

$$\tau^- \to \Lambda \pi^-, \overline{\Lambda} \pi^-$$

Belle II

$$\Upsilon(2S) \to \ell^\pm \tau^\mp$$

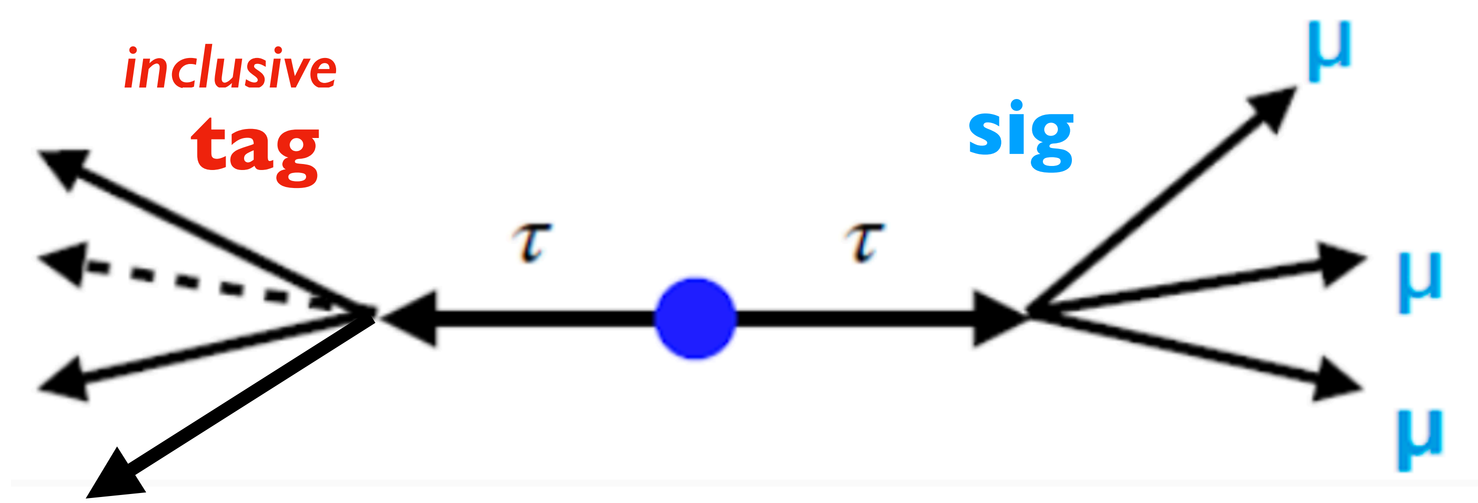
BELLE

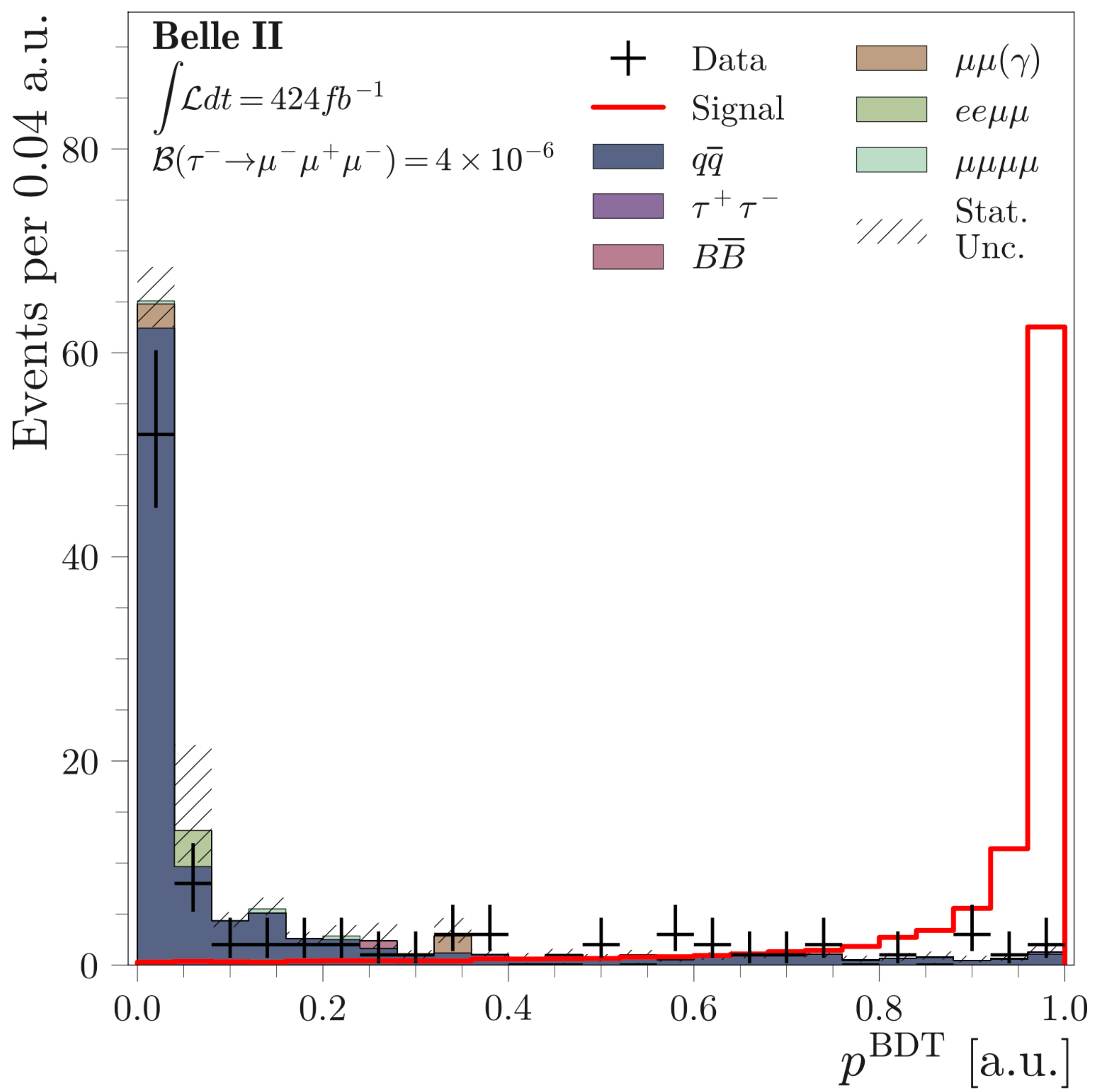
$\tau^+ \to \mu^+\mu^-\mu^+$

- Belle II with 424 fb^{-1}
- two hemispheres
  - for τ_{sig} and τ_{tag}
  - separated by a plane $\perp \hat{\mathbf{n}}_T$ (thrust axis), maximizing T

$$T = \max_{\hat{\mathbf{n}}_T} \left(\frac{\sum_i |\mathbf{p}^*{}_i \cdot \hat{\mathbf{n}}_T|}{\sum_i |\mathbf{p}^*{}_i|} \right)$$

- inclusive tagging
  - allow 3×1 and 3×3 (measure all the neutrals, too)
  - signal optimization and background rejection by multi-variate analysis (BDT)





$\tau^+ \to \mu^+\mu^-\mu^+$

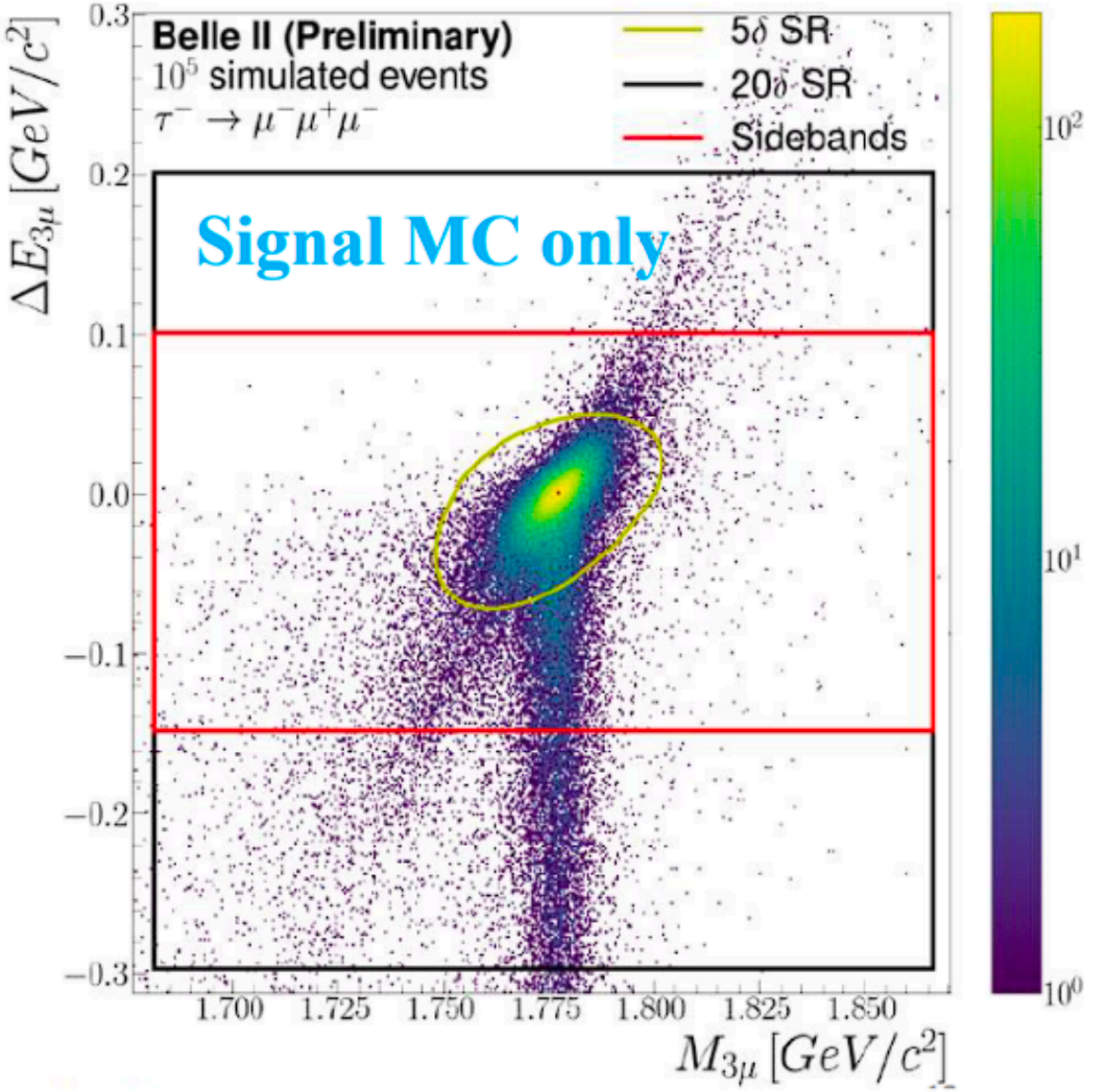
2D analysis for signal extraction

- variables

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$

$$\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{\text{beam}}^{CM}$$

- analysis regions
  - $\pm 20\sigma$ analysis region
  - sideband — for bkgd. estimation
  - 5σ signal ellipse ("SR", blinded)

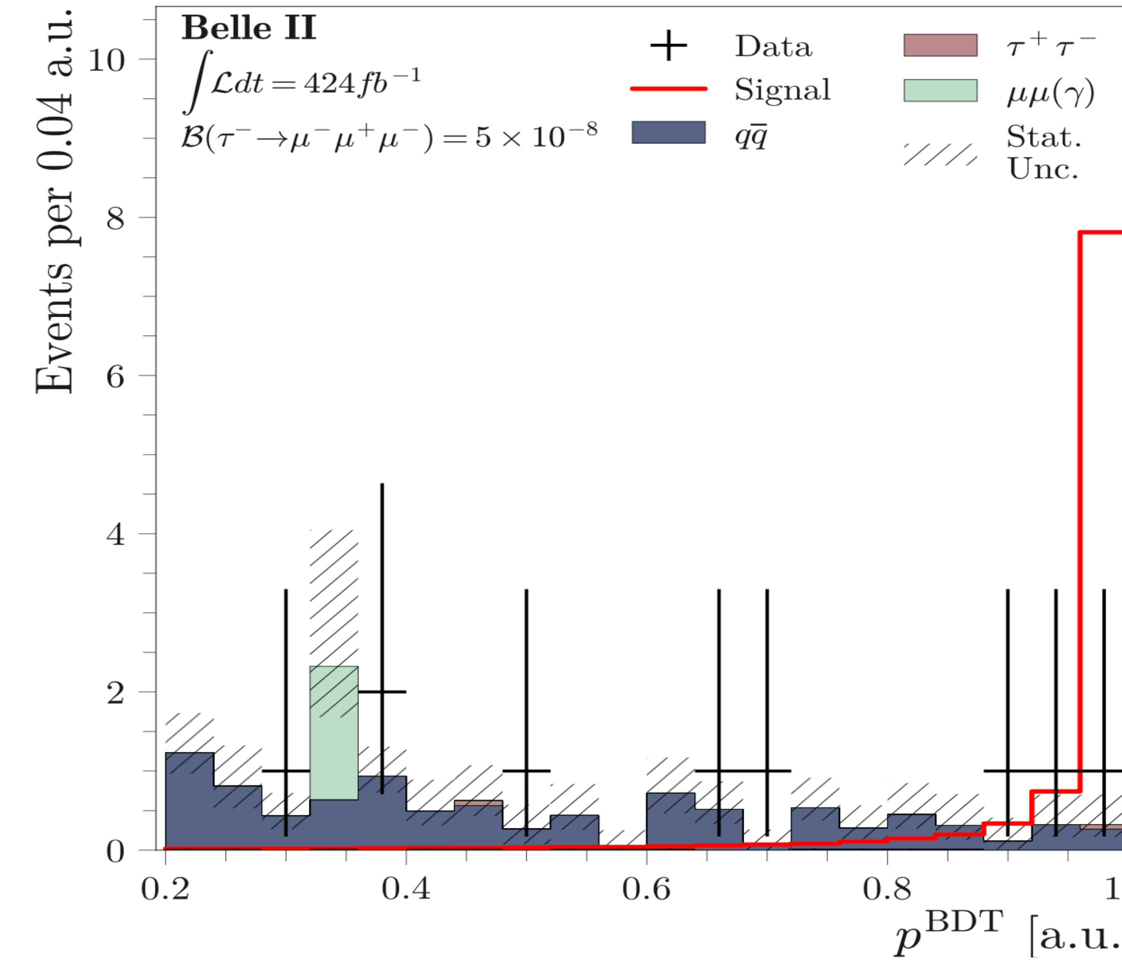


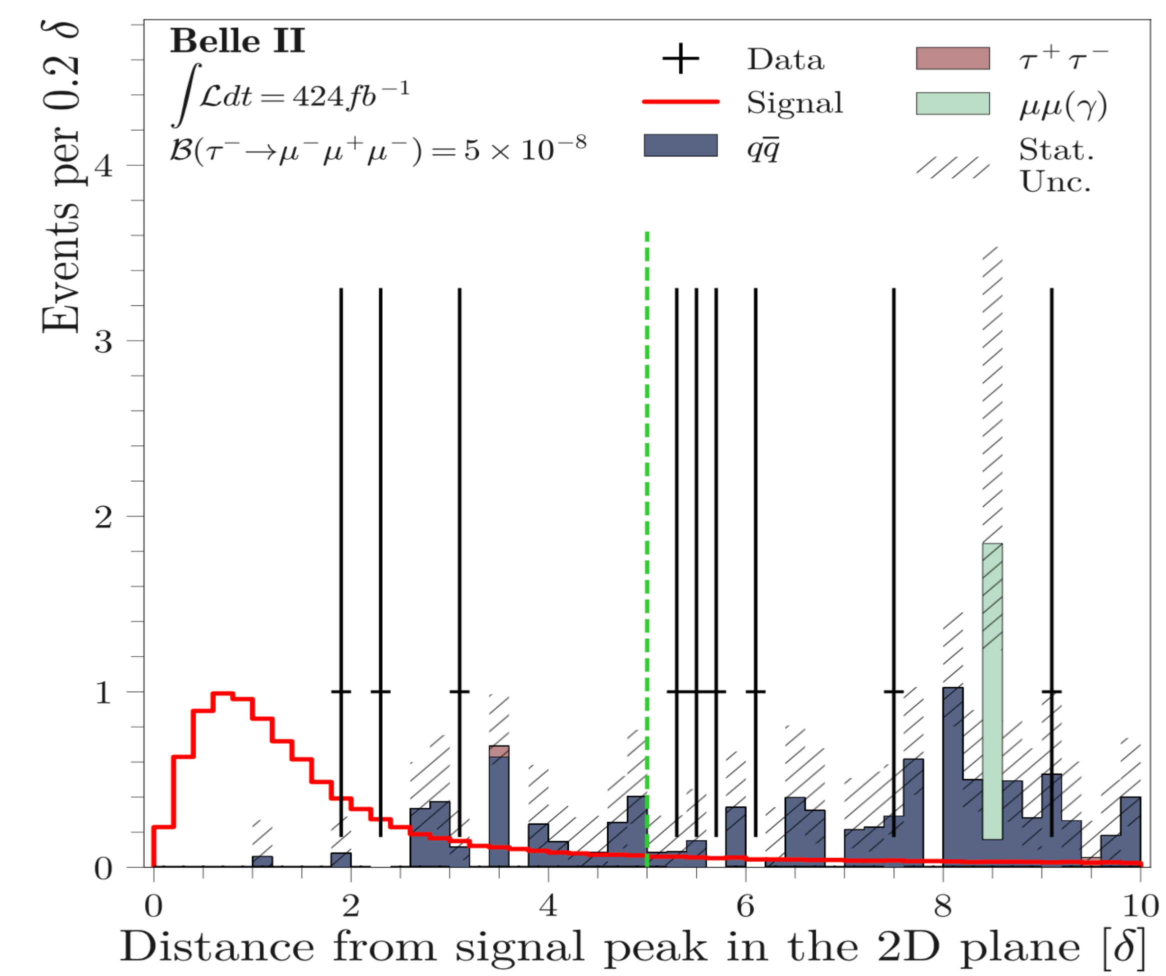
$\tau^+ \to \mu^+\mu^-\mu^+$

- check agreement b/w data and MC for the BDT output
  - [SB] $2.0^{+0.7}_{-0.5}$ (MC) vs. 3 events (data)
- expected N(background)
  - data-driven method using 3 regions
    $N_A = 4$, outside SR with $0.2 < p^{\text{BDT}} < 0.85$
    $N_B = 2$, inside SR with $0.2 < p^{\text{BDT}} < 0.85$
    $N_C = 1$, outside SR with $p^{\text{BDT}} > 0.9$

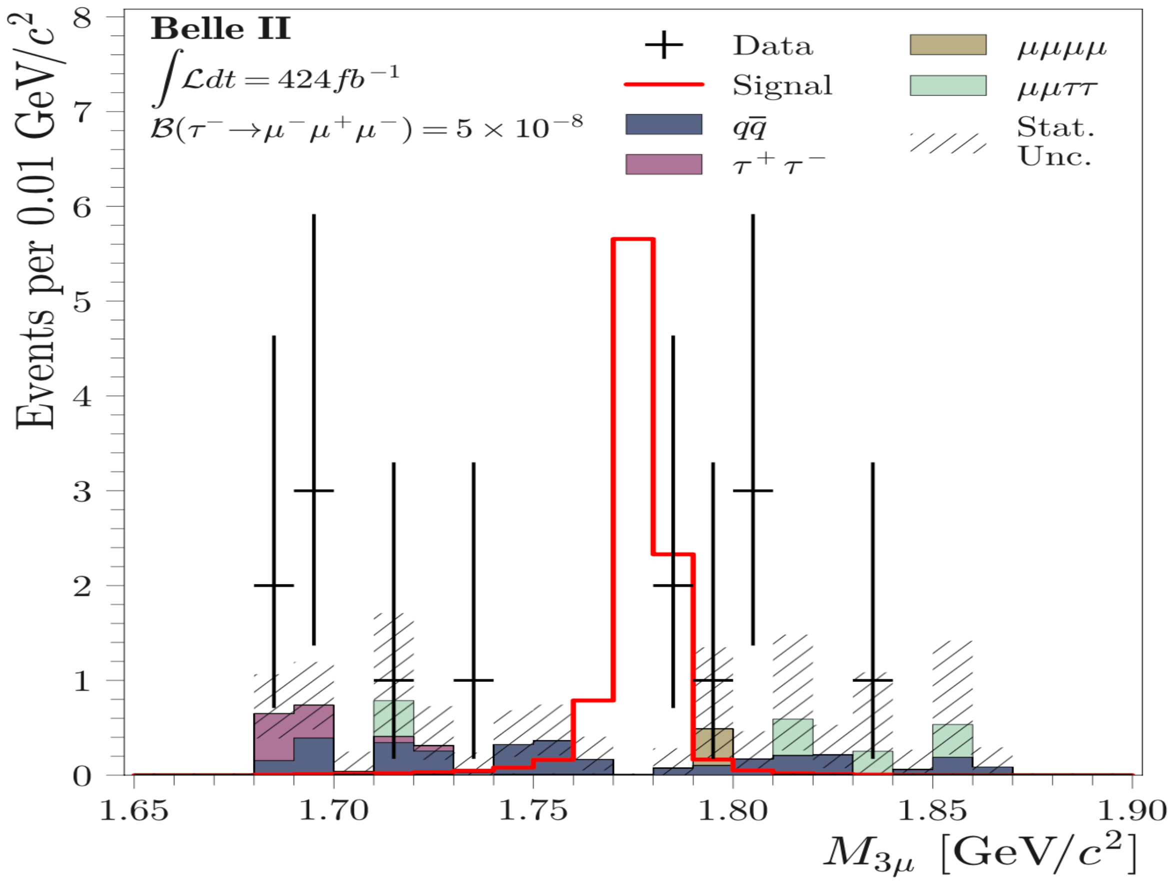
$$N_{\text{exp}} = N_C \times \frac{N_B}{N_A}$$

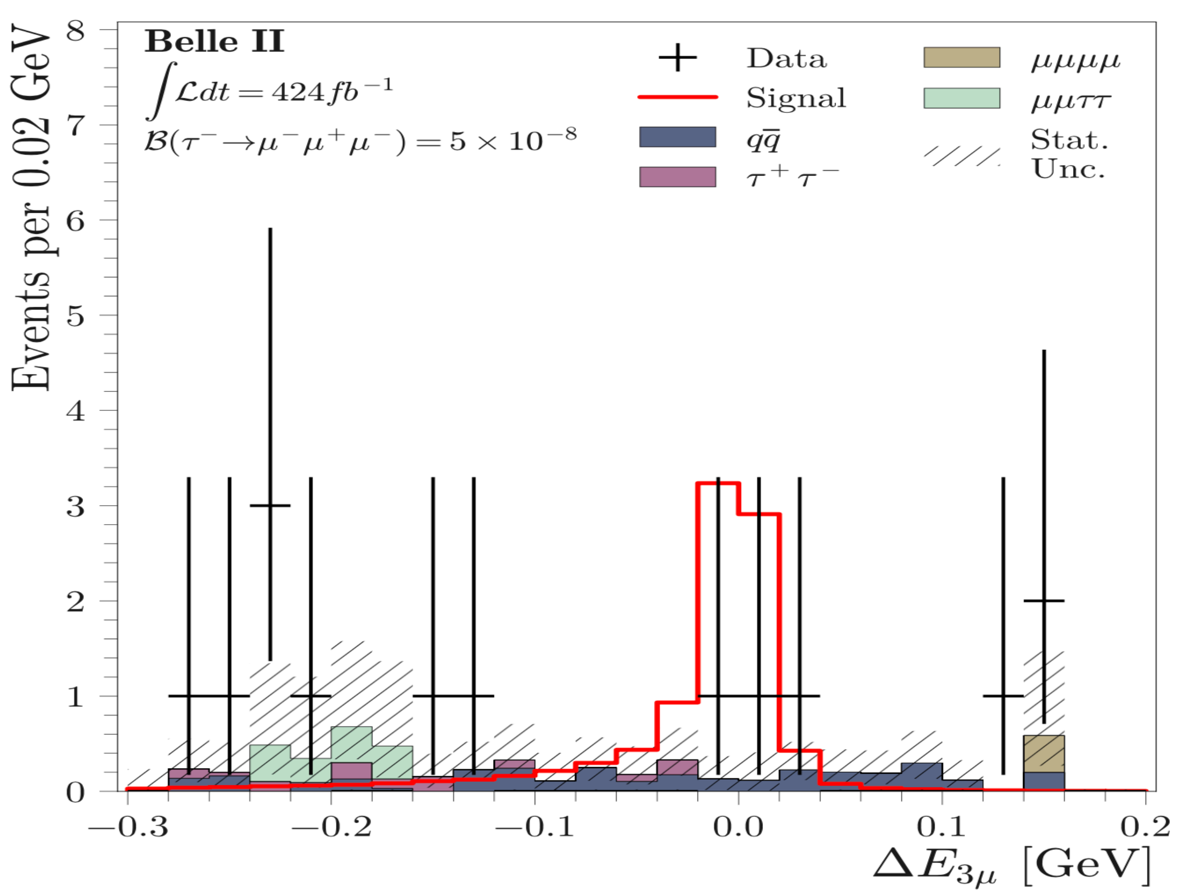
  - $N_{\text{exp}} = 0.7^{+0.6}_{-0.5}$ (from pseudoexperiments assuming Poisson dist. for N_A, N_B, N_C)

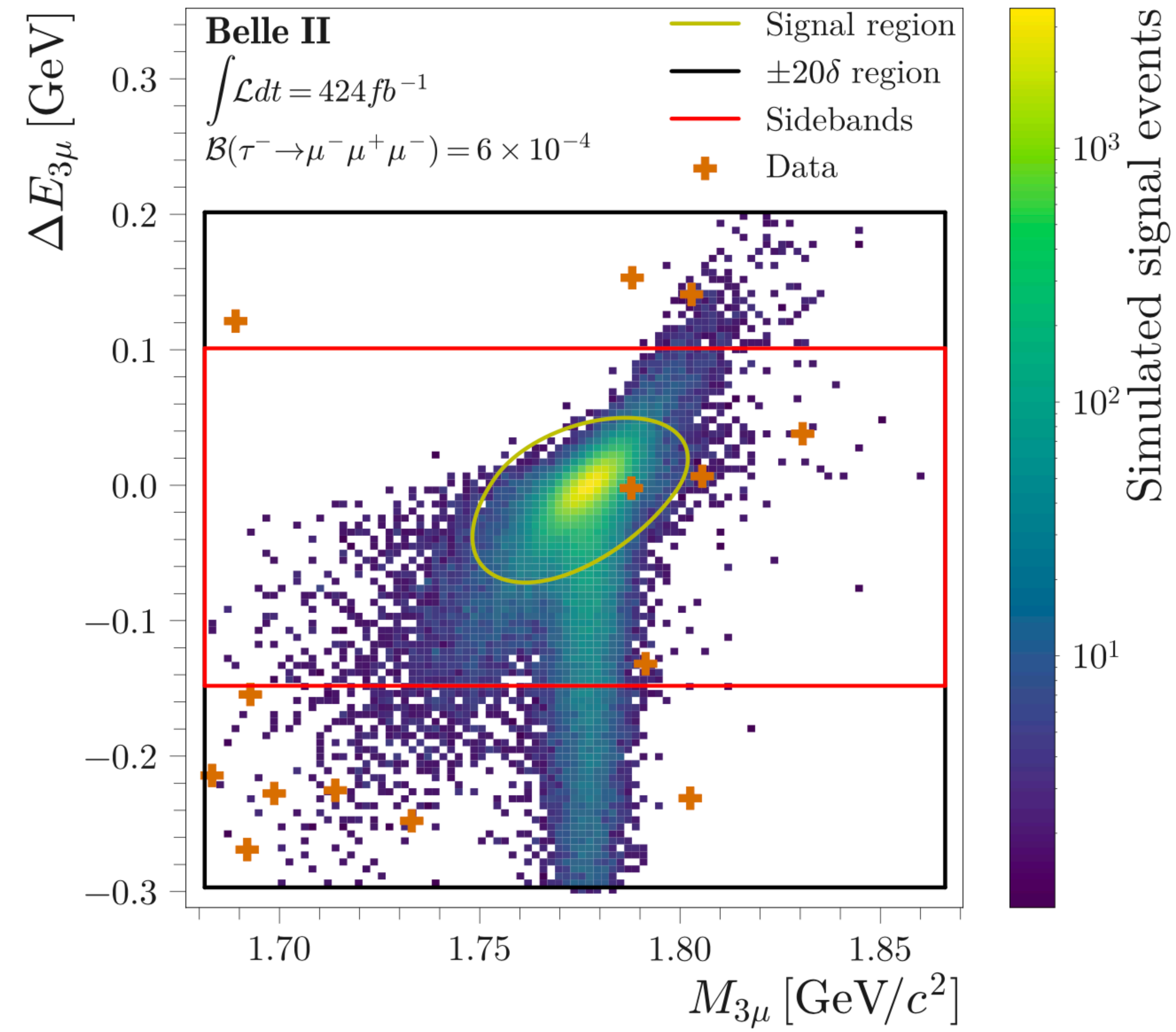




$\tau^+ \to \mu^+\mu^-\mu^+$ Result



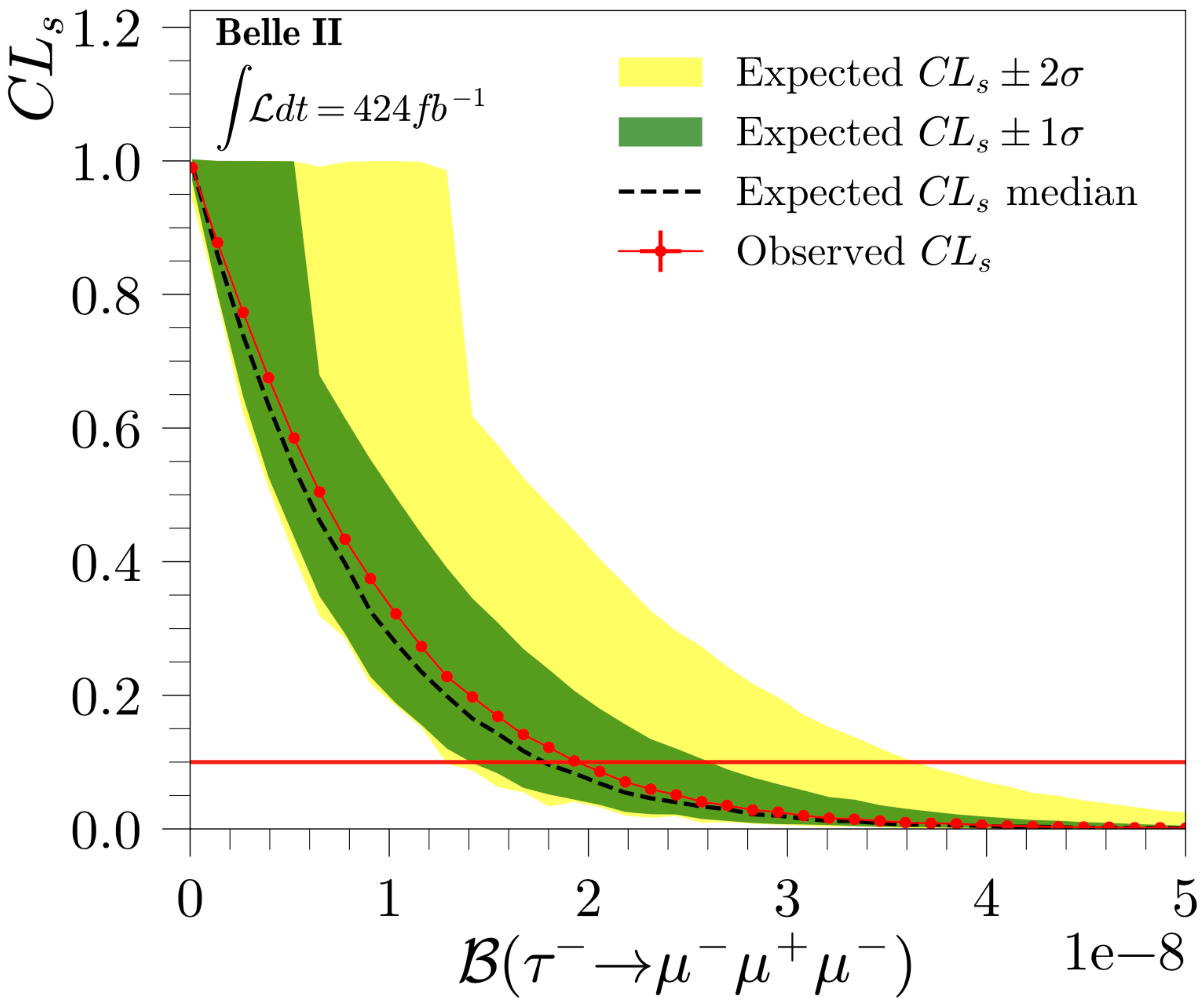




$$\mathscr{B}(\tau^+ \to \mu^+\mu^-\mu^+) = (2.1^{+5.1}_{-2.4} \pm 0.4) \times 10^{-9}$$

- dominant syst. uncertainties from momentum scale (16 %), signal region ($^{+2.9}_{-3.9}$ %)

Upper limit of $\mathscr{B}(\tau^+ \to \mu^+\mu^-\mu^+)$



- UL estimated with CLs method (*modified frequentist* in RooStat)
  - 5×10^4 pseudo-experiments at 40 uniform points in the BF range (0-5) $\times 10^{-8}$
- observed (expected) limit: $\mathscr{B} < 1.9\ (1.8) \times 10^{-8}$
  - most stringent to date

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$\tau^+ \to \ell^+ V^0$

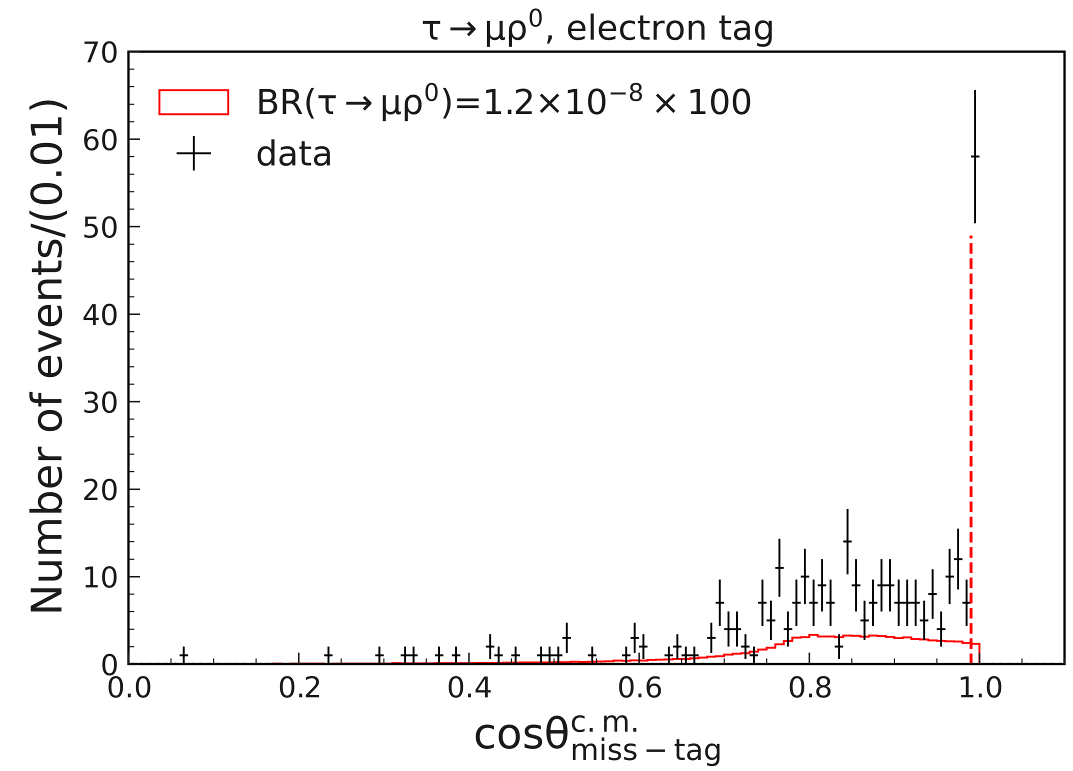
980 fb^{-1} of Belle data (126 fb^{-1} more than previous)

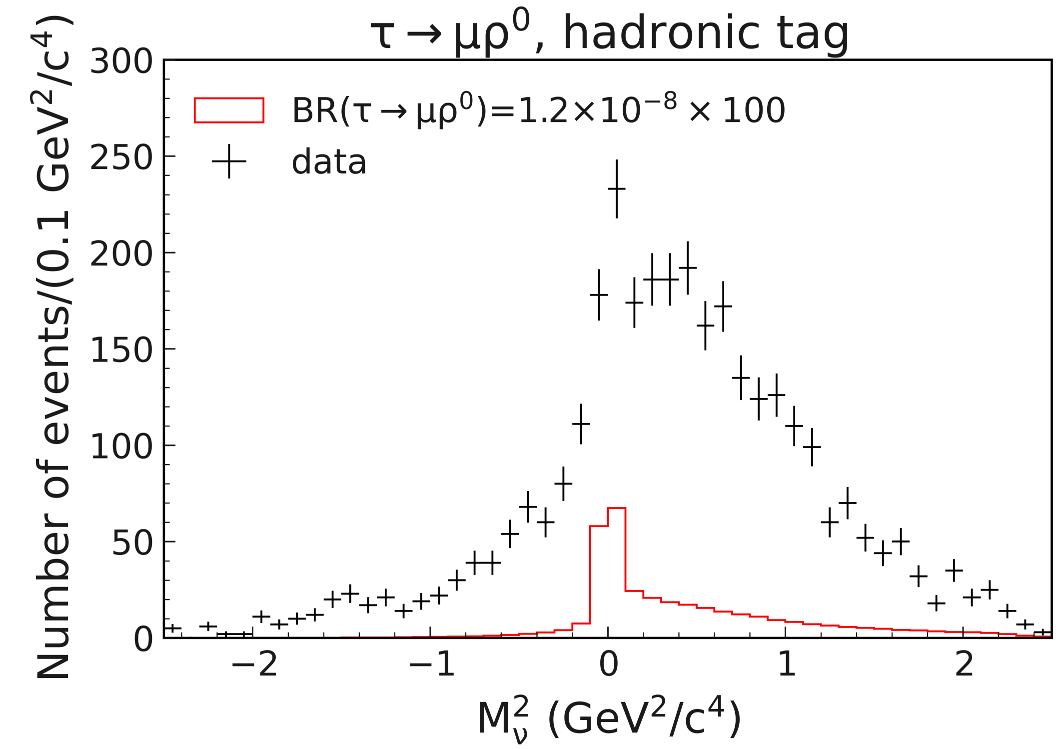
Motivation

- $\tau^+ \to \mu^+ \phi$ thought to be a sensitive probe for LQ models
- some models (unparticle, type-III seesaw, littlest Higgs) predict $\mathscr{B} \sim \mathcal{O}(10^{-10} - 10^{-8})$

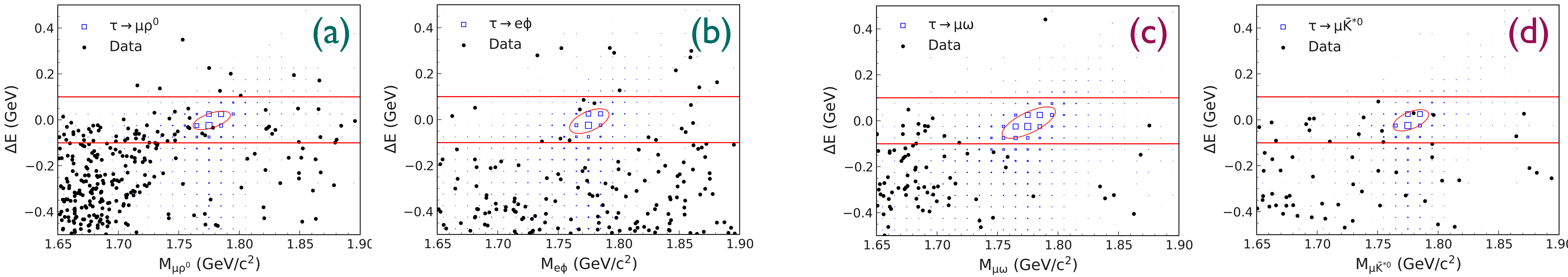
Analysis feature

- tag side: $\ell^\pm \nu\nu$, $\pi^\pm \nu$, $\pi^\pm \pi^0 \nu$, $\pi^\pm \pi^0 \pi^0 \nu$, $\pi^\pm \pi^\mp \pi^\pm \nu$
- signal side: $\ell = e, \mu$ and $V = \rho^0, \phi, \omega, K^{*0}, \overline{K}^{*0}$
- reject missing particle(s) (any missing particle should be in the tag side)
  - ✓ $\cos\theta^{\text{cm}}_{\text{miss-tag}} > 0$ and additional cuts depending on mode
- BDT to further reduce the remaining bkgd.
  - ✓ M_{V^0}, M_ν^2, $P_\nu^{\text{c.m.}}$, T, P_ℓ^{sig}, $E_{\text{tag}}^{\text{hemi}}$, $\cos\theta^{\text{c.m.}}_{\text{miss-tag}}$
  - ✓ (categorical) τ decay modes, collision energy
  - ✓ (additionally for $\ell^+\omega$) $p_{\pi^0}^{\text{sig}}$, E_γ^{low}





$\tau^+ \to \ell^+ V^0$



	Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)
(a)	$\tau^- \to \mu^- \rho^0$	7.78	0.95±0.20(stat.) ±0.11(syst.)	4.6	0	< 1.7
	$\tau^- \to e^- \rho^0$	8.49	0.80±0.27(stat.) ±0.02(syst.)	4.4	1	< 2.2
	$\tau^- \to \mu^- \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3
(b)	$\tau^- \to e^- \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0
(c)	$\tau^- \to \mu^- \omega$	3.27	0.32±0.23(stat.) ±0.03(syst.)	4.8	0	< 3.9
	$\tau^- \to e^- \omega$	5.41	0.74±0.43(stat.) ±0.01(syst.)	4.5	0	< 2.4
	$\tau^- \to \mu^- K^{*0}$	4.52	0.84±0.25(stat.) ±0.03(syst.)	4.3	0	< 2.9
	$\tau^- \to e^- K^{*0}$	6.94	0.54±0.21(stat.) ±0.12(syst.)	4.1	0	< 1.9
(d)	$\tau^- \to \mu^- \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.06(syst.)	4.3	1	< 4.2
	$\tau^- \to e^- \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.01(syst.)	4.1	0	< 1.7

"… the upper limits are improved by 30% on average …"

arXiv:2407.05117

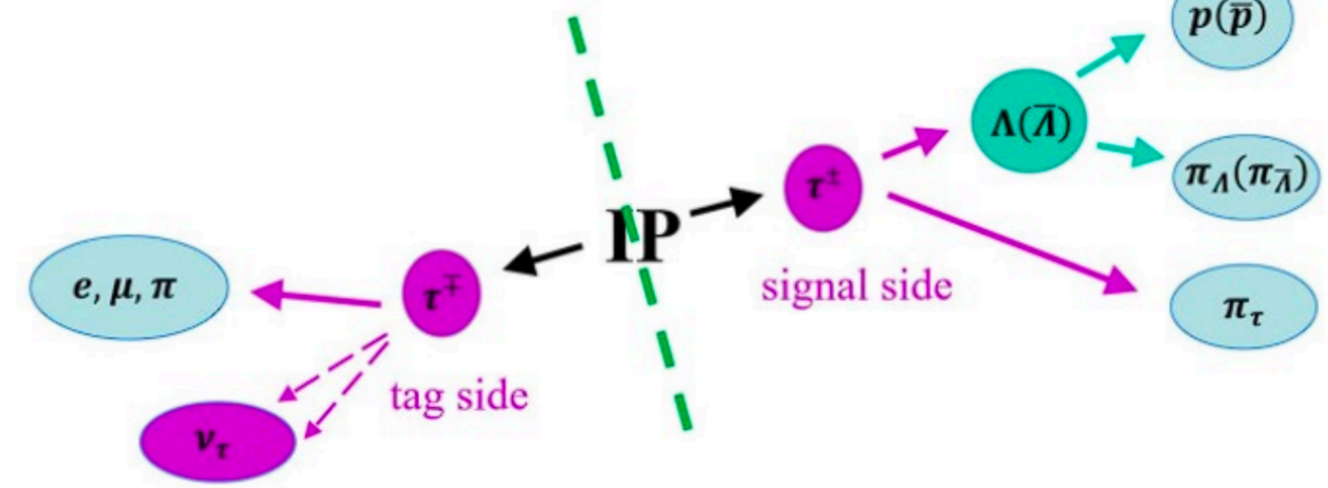
$\tau^- \to \Lambda\pi^-, \bar{\Lambda}\pi^-$

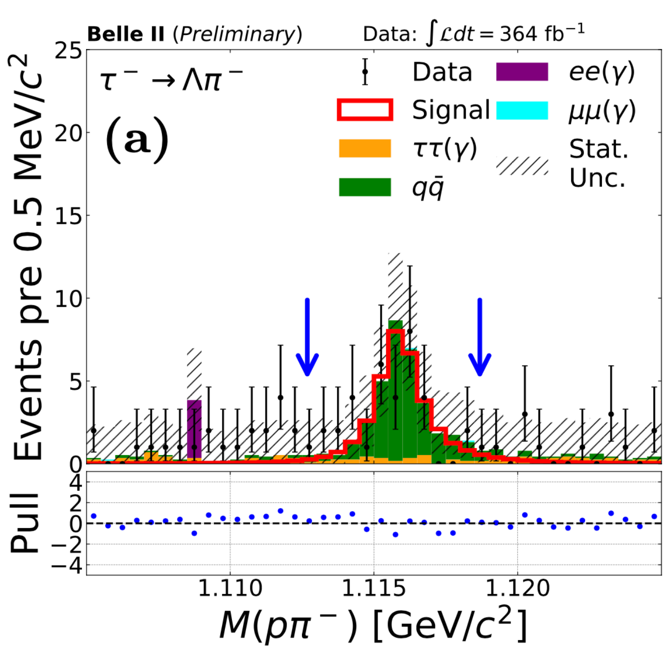
baryon-number-violating (BNV)

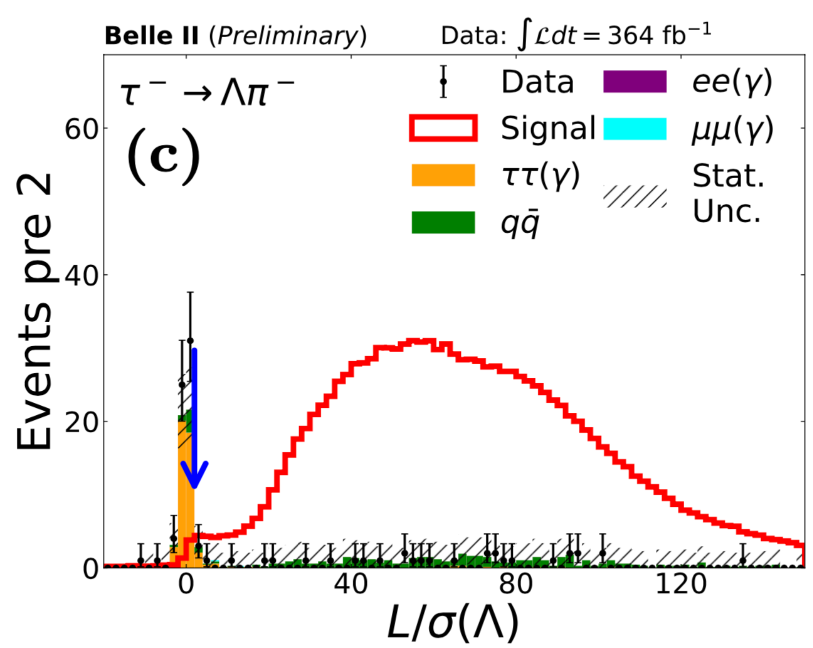
- in SM, baryon # (B) and lepton # (L) conservations are *accidental*
- but sphaleron processes could result in BNV & LNV, while preserving $B - L$
- some NP models predict BNV, with $|\Delta(B-L)| = 0, 2$

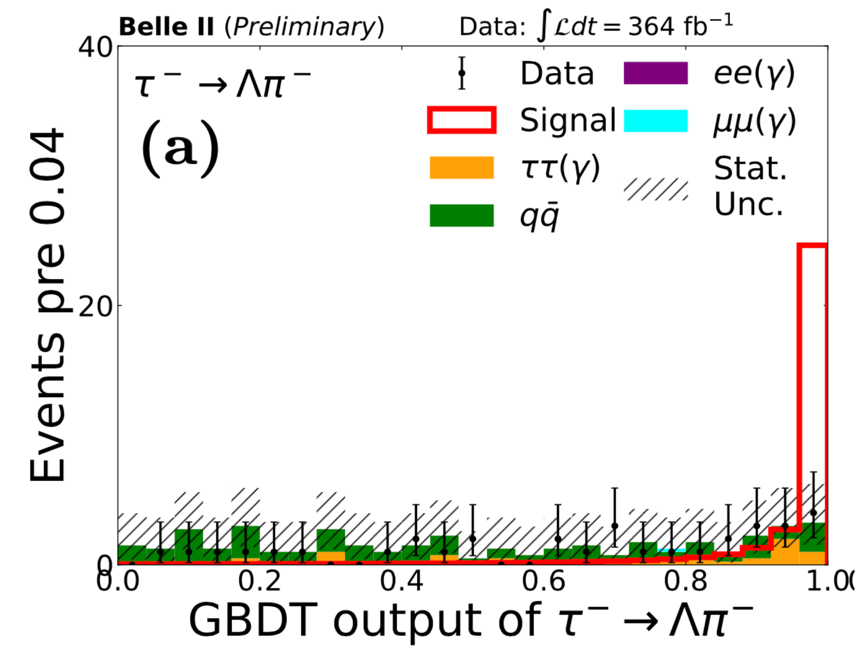
analysis approach

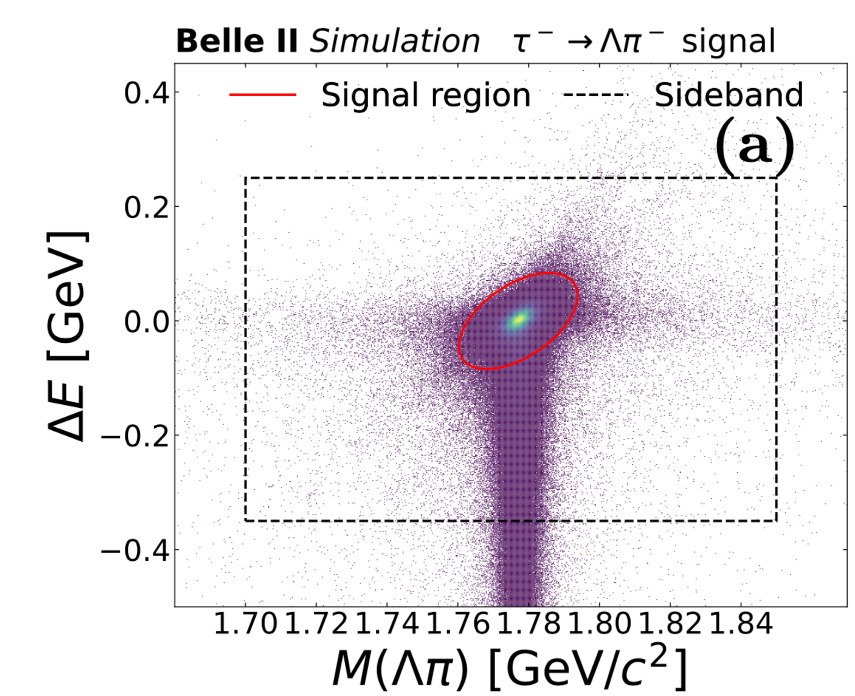
- use $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
- require 1-prong tag, resulting in 4 charged tracks
- signal selection and optimization by Gradient-BDT
- use sideband in $(M_{\Lambda\pi}, \Delta E)$ for bkgd. assessment











$\tau^- \to \Lambda\pi^-, \overline{\Lambda}\pi^-$ Result

Signal counting in $(M_{\Lambda\pi}, \Delta E)$

- efficiency: 9.5% (9.9%) for $\tau^- \to \Lambda\pi^-$ ($\overline{\Lambda}\pi^-$)
- $N_{\rm SB}^{\rm sim} = 3.2^{+1.7}_{-1.2}$ ($5.5^{+2.1}_{-1.6}$) for $\tau^- \to \Lambda\pi^-$ ($\overline{\Lambda}\pi^-$)
- 7 (6) events in the SB for $\tau^- \to \Lambda\pi^-$ ($\overline{\Lambda}\pi^-$), resulting in $N_{\rm exp} = 1.0^{+1.3}_{-1.1}$ (0.5 ± 0.6) for background
- zero event observed in each mode

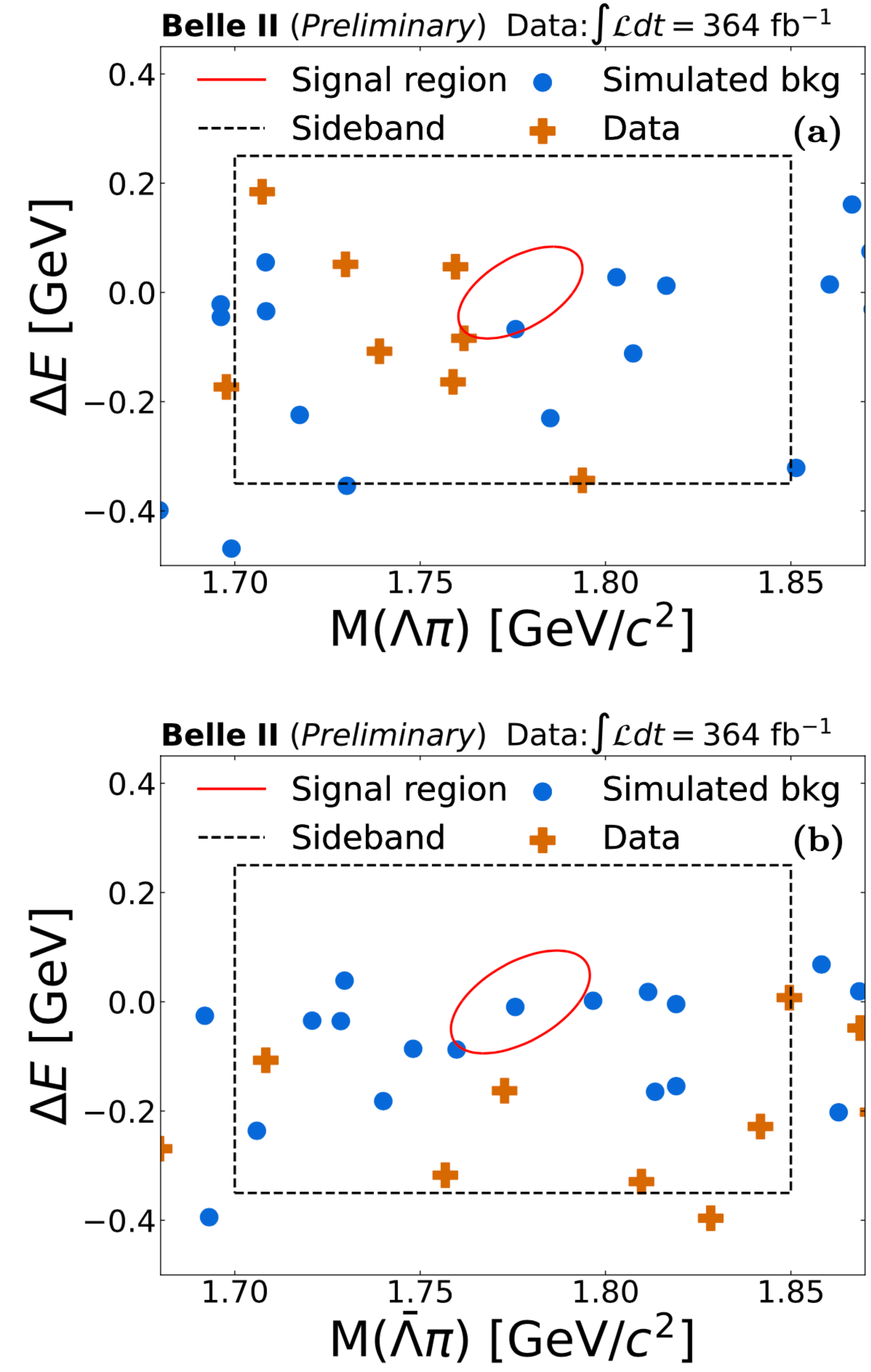
branching fractions

- dominant systematic source: hadron ID (~2.2%)

$$\mathscr{B}(\tau^- \to \Lambda\pi^-) = (-2.5^{+4.1+1.9}_{-3.7-1.4}) \times 10^{-8} < 4.7 \times 10^{-8}$$

$$\mathscr{B}(\tau^- \to \overline{\Lambda}\pi^-) = (-1.2 \pm 2.8^{+0.9}_{-0.5}) \times 10^{-8} < 4.3 \times 10^{-8}$$

- world's most stringent BF upper limits



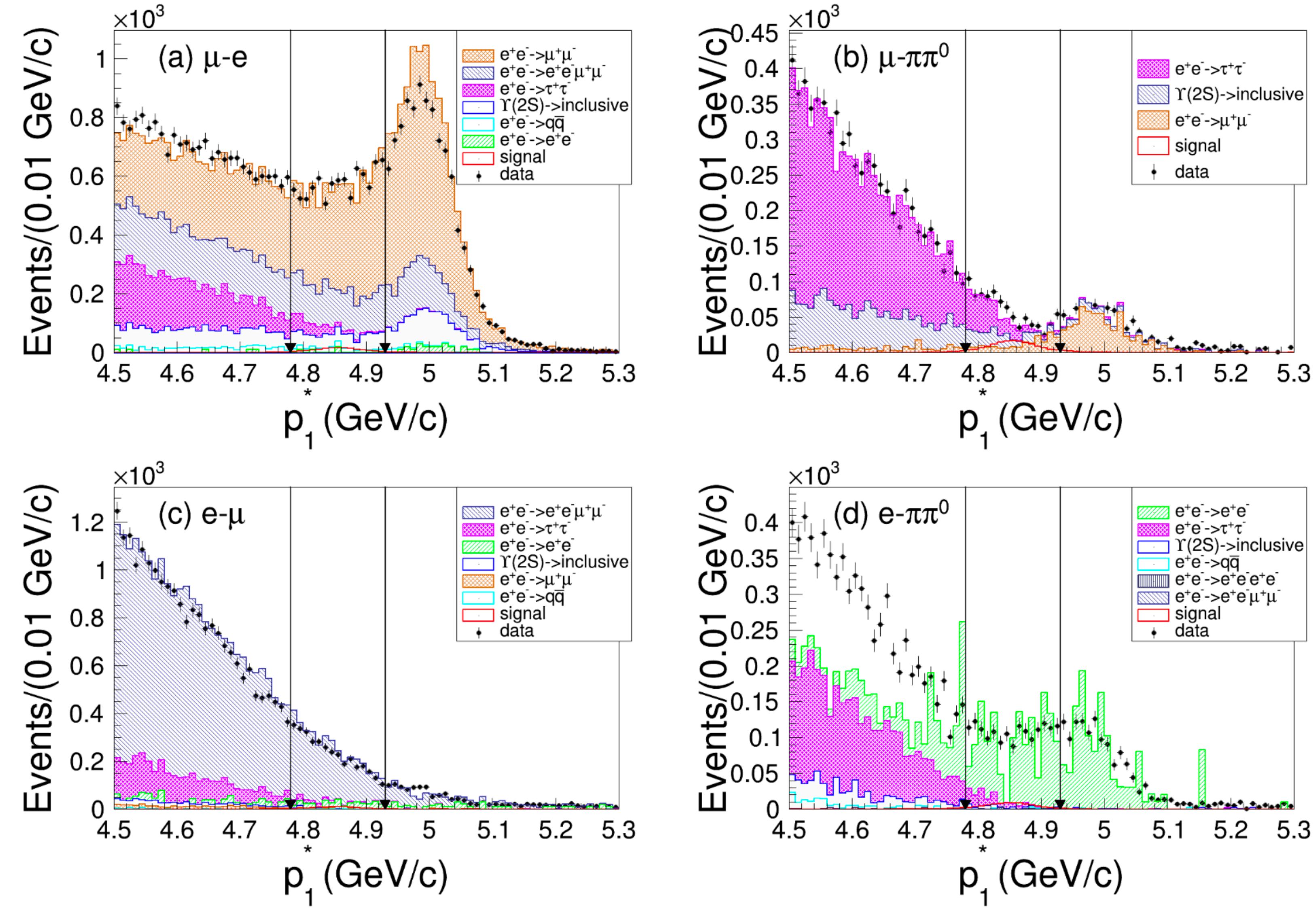
$\Upsilon(2S) \to \ell^\pm \tau^\mp$

Motivations

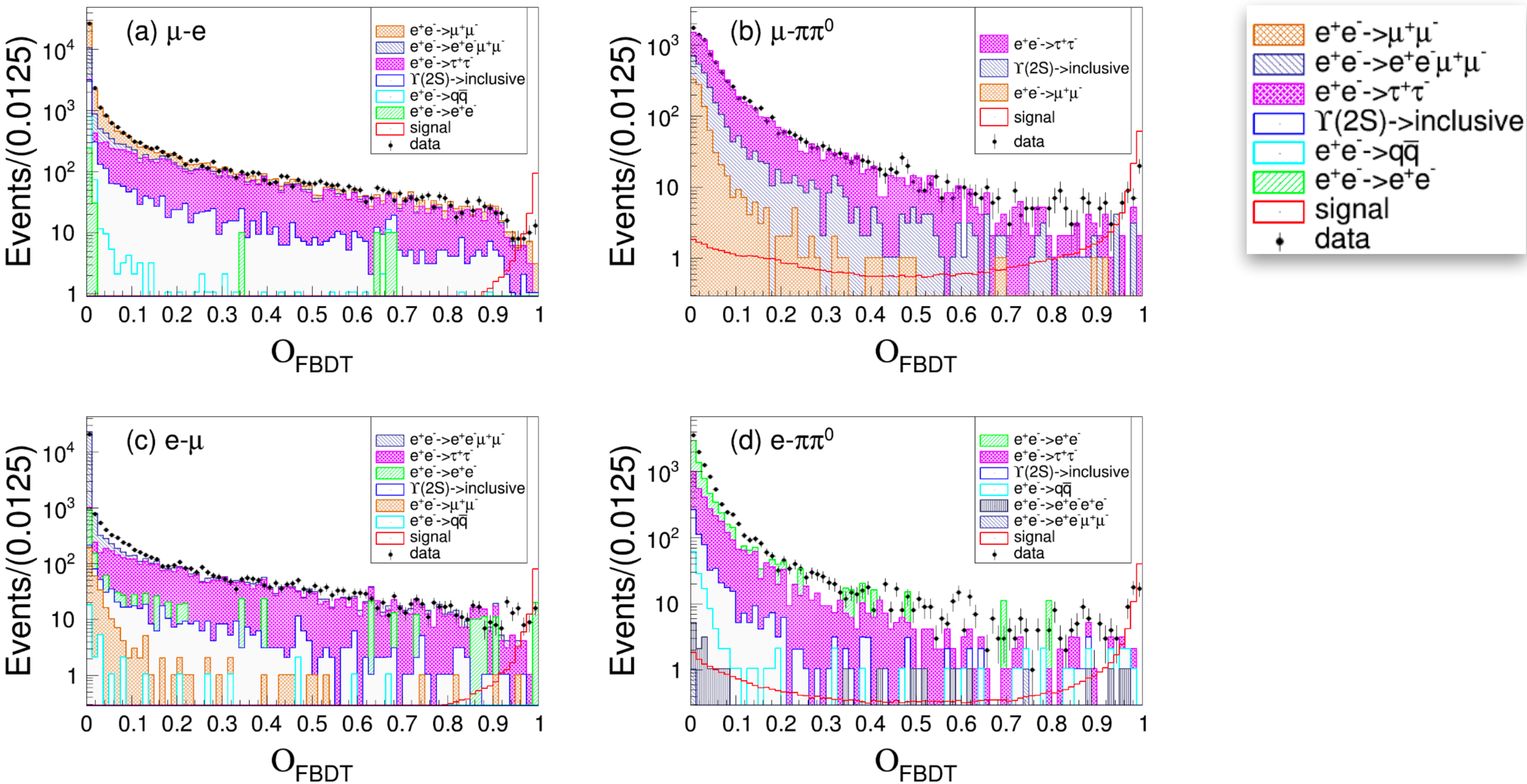
- 2-body CLFV decay of a quarkonium
- can provide complementary constraints on the Wilson coefficients of the $\mathscr{L}_{\text{eff}}$ of new physics models (D.E. Hazard and A.A. Petrov, PRD 94 (2016) 074023)

Analysis features

- use Belle data with 25 fb^{-1} @ $\Upsilon(2S)$ in Belle II analysis framework (B2BII)
- high-momentum primary lepton (ℓ_1) from $\Upsilon(2S) \to \ell_1^\pm \tau^\mp$
- use τ^+ decays to $\ell_2^+ \nu \overline{\nu}$ or $\pi^+ \overline{\nu}$
- ℓ_2 to have different flavor w.r.t. ℓ_1, to suppress copious bkgd. from Bhabha processes
- FastBDT for further background suppression



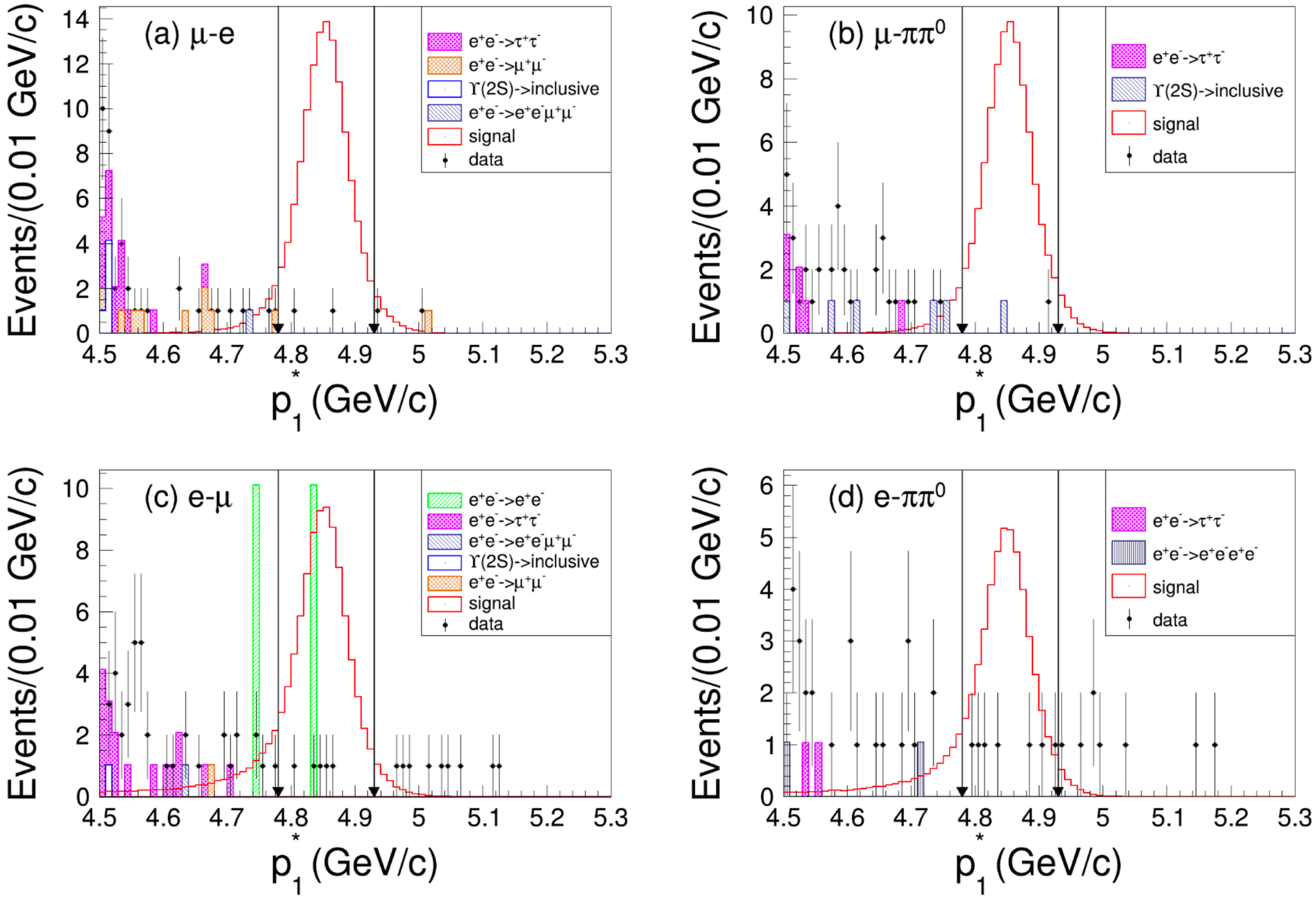
$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$



O_{FBDT} distributions for the four channels; signal component assumes $\mathscr{B} = 1 \times 10^{-5}$

$\Upsilon(2S) \to \ell^{\pm}\tau^{\mp}$ Results

p_1^* distributions after $O_{\rm FBDT} > 0.94$



Modes	$\epsilon_{\rm sig}$ (%)	$N_{\rm exp}^{\rm bkg}$	$N_{\rm obs}$
$\Upsilon(2S) \to \mu^{\mp}\tau^{\pm}$	12.3 ± 0.8	3.9 ± 1.8	3
$\Upsilon(2S) \to e^{\mp}\tau^{\pm}$	8.1 ± 1.1	5.9 ± 2.6	12

$$\mathcal{B}(\Upsilon(2S) \to \mu\tau) < 0.23 \times 10^{-6}$$

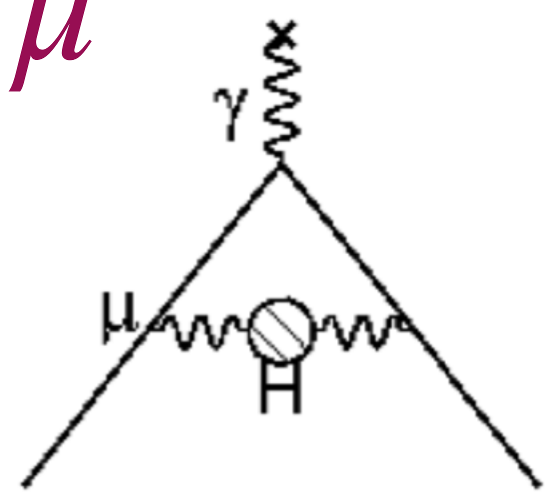
$$\mathcal{B}(\Upsilon(2S) \to e\tau) < 1.12 \times 10^{-6}$$

@ 90% CL

Belle (this) results are 14 (3) times more stringent than BaBar (PRL, 2010)

For 'light new physics'

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ ***for*** a_μ^{HVP}



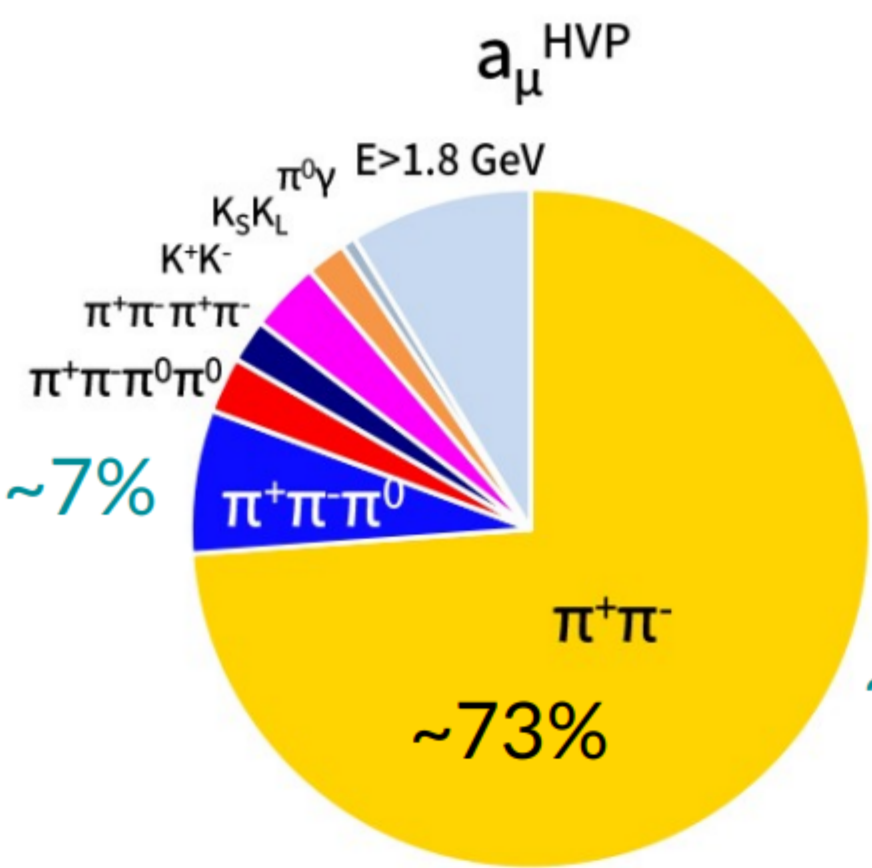
connections to muon (g-2)

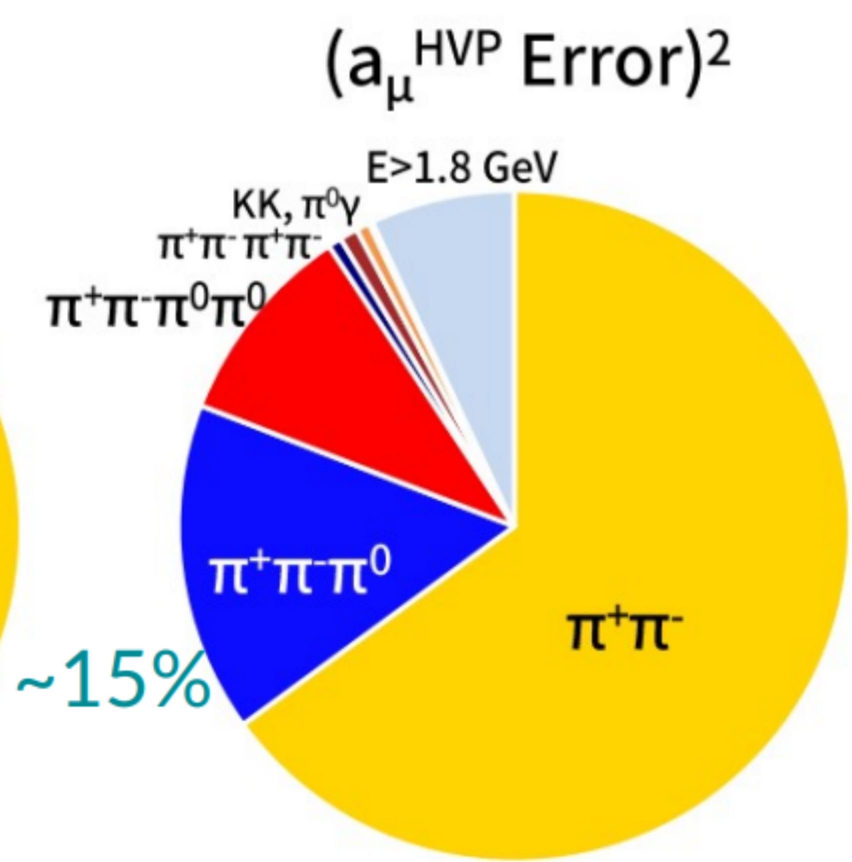
$$a_\mu = \frac{(g-2)_\mu}{2} = a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{QCD}}$$

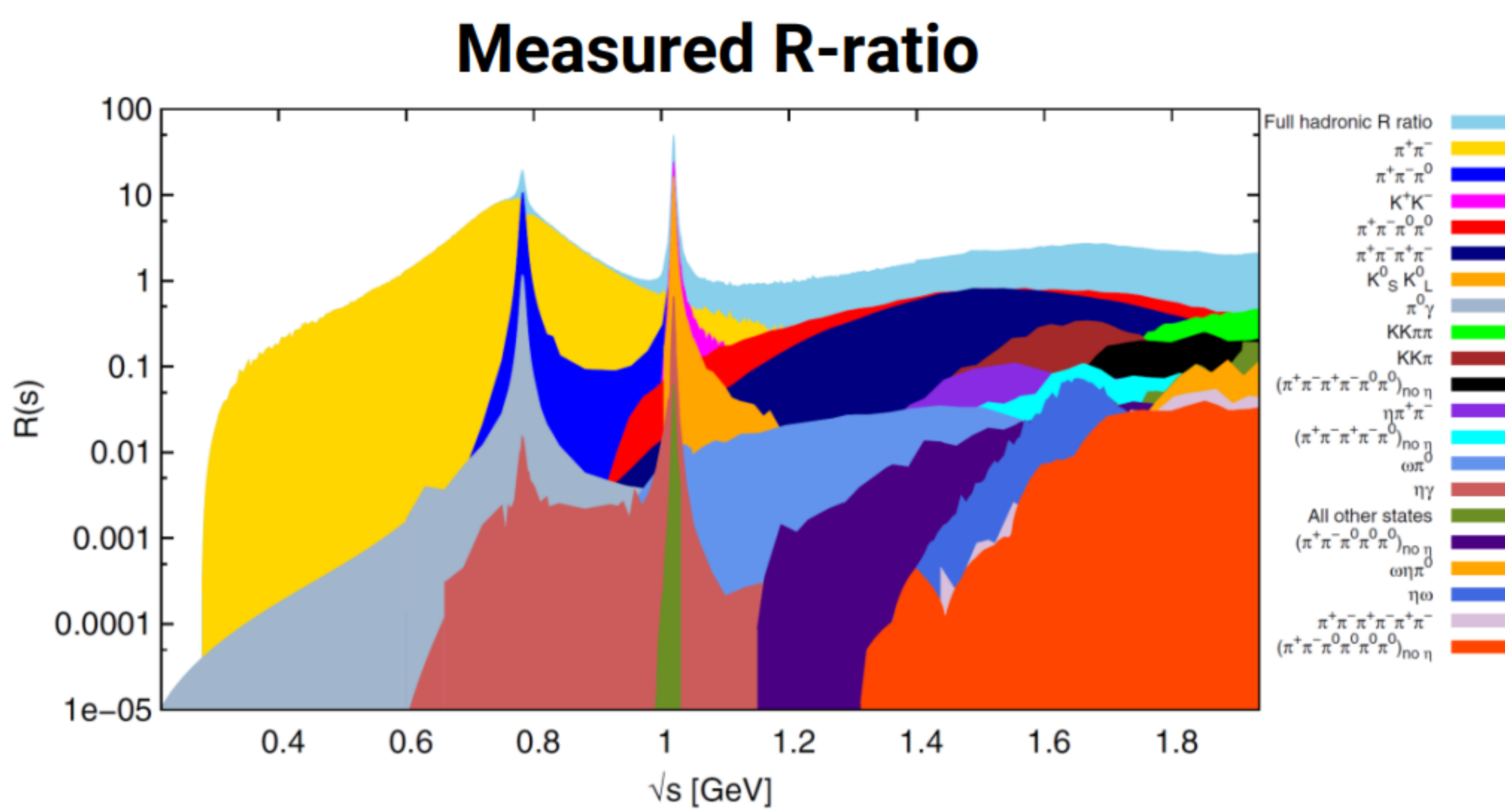
$$a_\mu^{\mathrm{QCD}} = a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{H,LBL}}$$

(82%) (18%)

$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha}{3\pi^2}\int_{m_\pi^2}^{\infty} \frac{K(s)}{s} R_{\mathrm{had}}(s)\, ds, \quad R_{\mathrm{had}}(s) = \frac{\sigma_0(e^+e^- \to \mathrm{hadrons})}{\sigma_{\mathrm{pt}}(e^+e^- \to \mu^+\mu^-)};$$





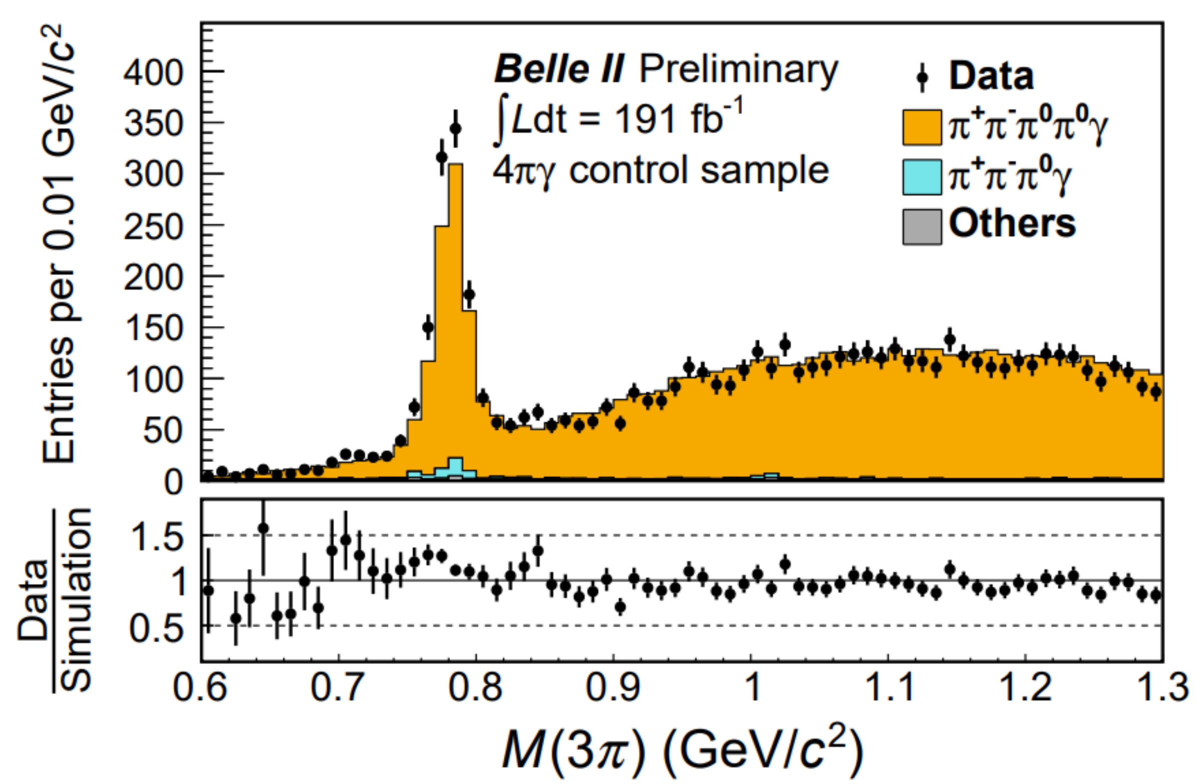


(a) The hadronic R-ratio.

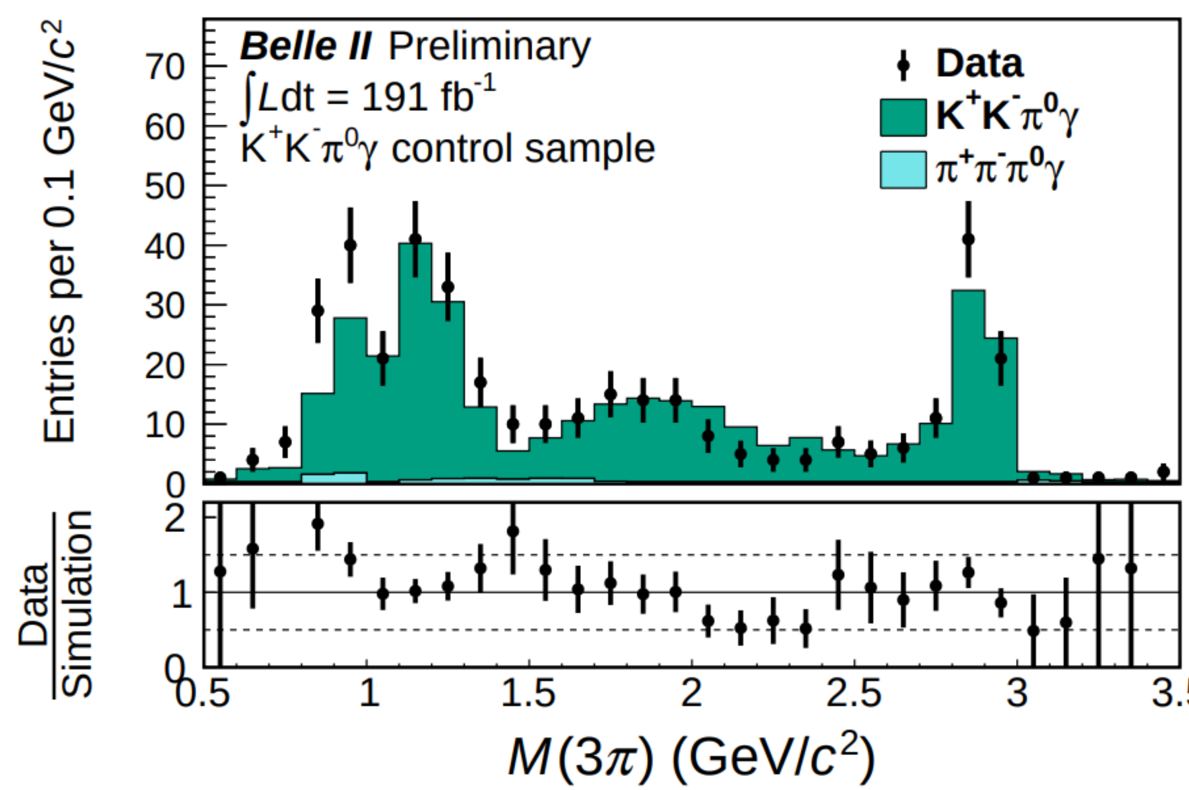
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

- Study $e^+e^- \to \pi^+\pi^-\pi^0$ decays in $\mathscr{L} = 191\ \mathrm{fb}^{-1}$
- as a function of $\sqrt{s'}$ by using **ISR** technique
  - reconstruct $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\mathrm{ISR}}$, for $0.62 < \sqrt{s'} = M(3\pi) < 3.50$ GeV
- Kinematic fit for background suppression
  - constrain $(E, \vec{p})$ of $\pi^+\pi^-\pi^0\gamma_{\mathrm{ISR}}$ to that of e^+e^- beams
- Validation ("scale factor") of backgrounds in control samples

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$



$e^+e^- \to K^+K^-\pi^0\gamma$

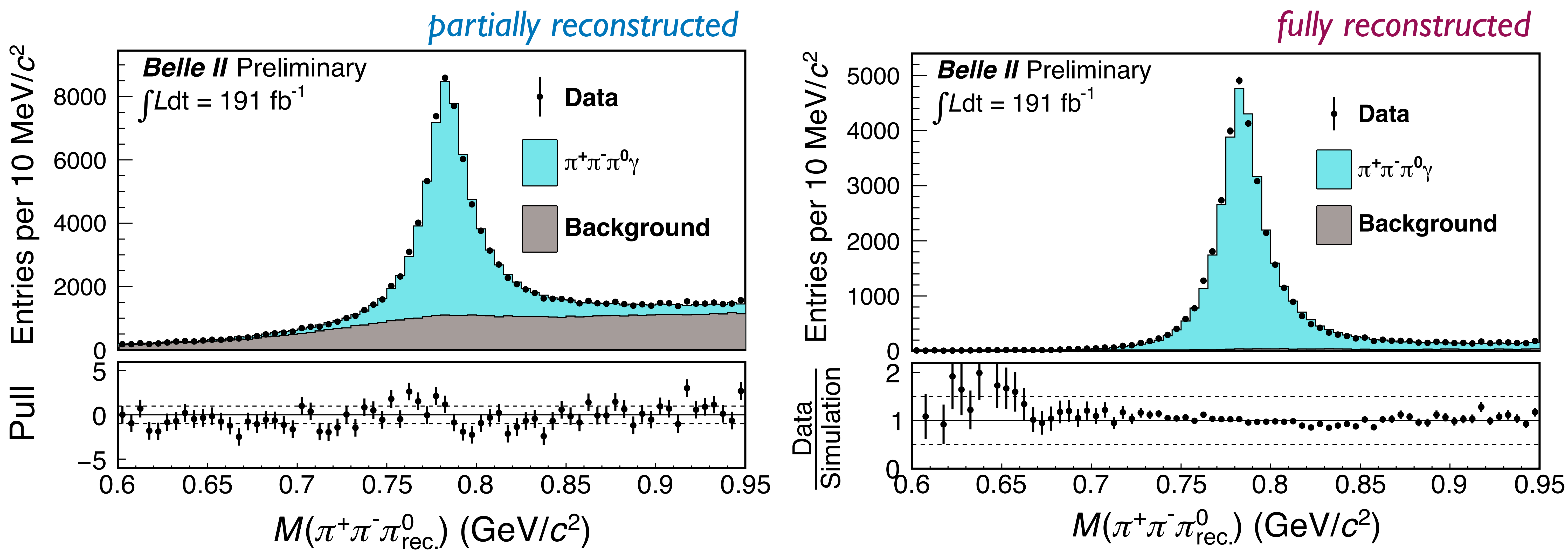


arXiv:2404.04915
accepted for PRD

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

$$\varepsilon(\pi^0) = \frac{N_{\mathrm{full}}(\gamma_{\mathrm{ISR}}\pi^+\pi^-\pi^0)}{N_{\mathrm{partial}}(\gamma_{\mathrm{ISR}}\pi^+\pi^-)}$$

- π^0 efficiency as a major analysis challenge
- The $\varepsilon(\pi^0)$ is determined to an accuracy of ~1% by comparing full- and partial-reconstruction in the $\omega \to \pi^+\pi^-\pi^0$ region



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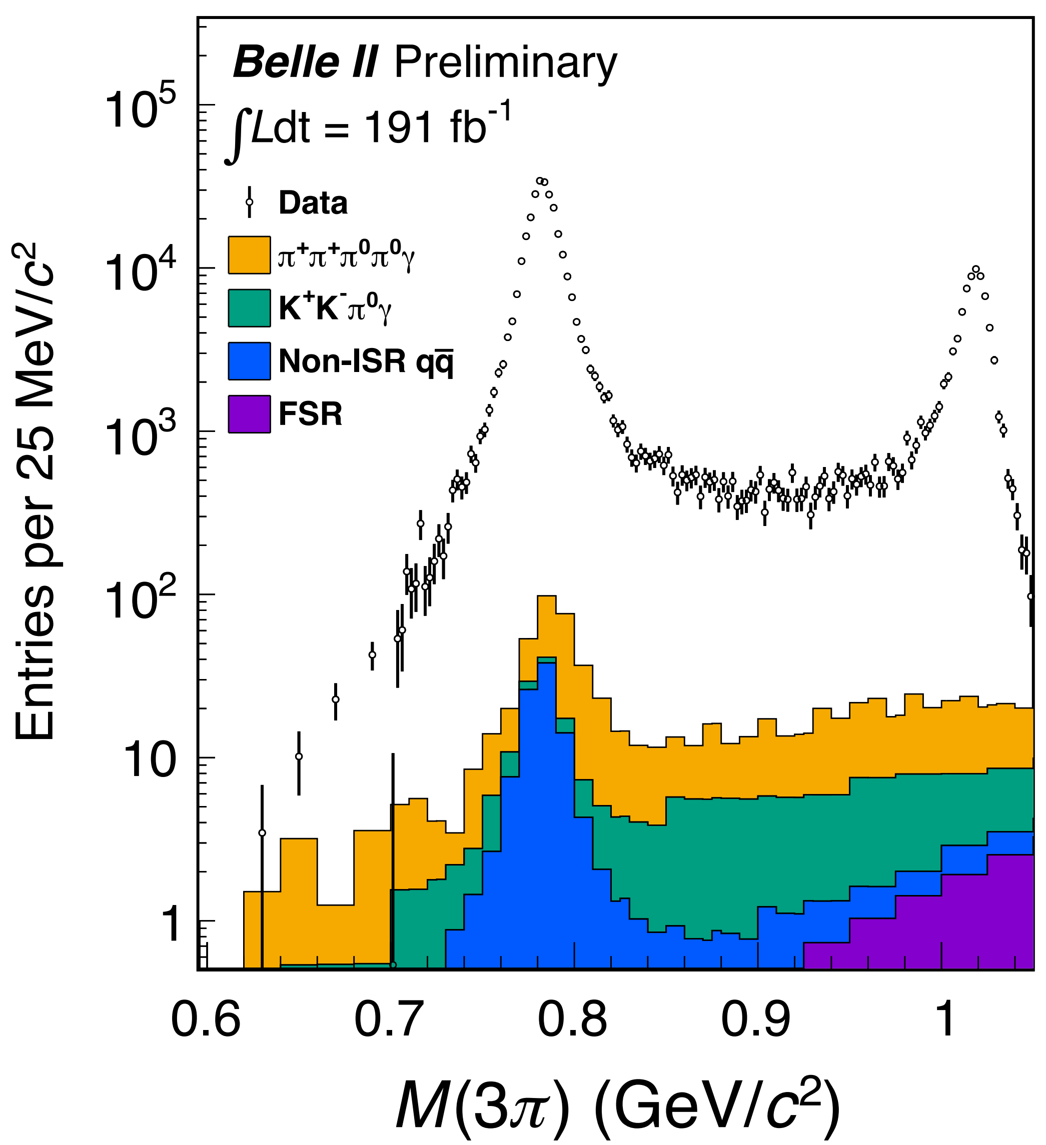
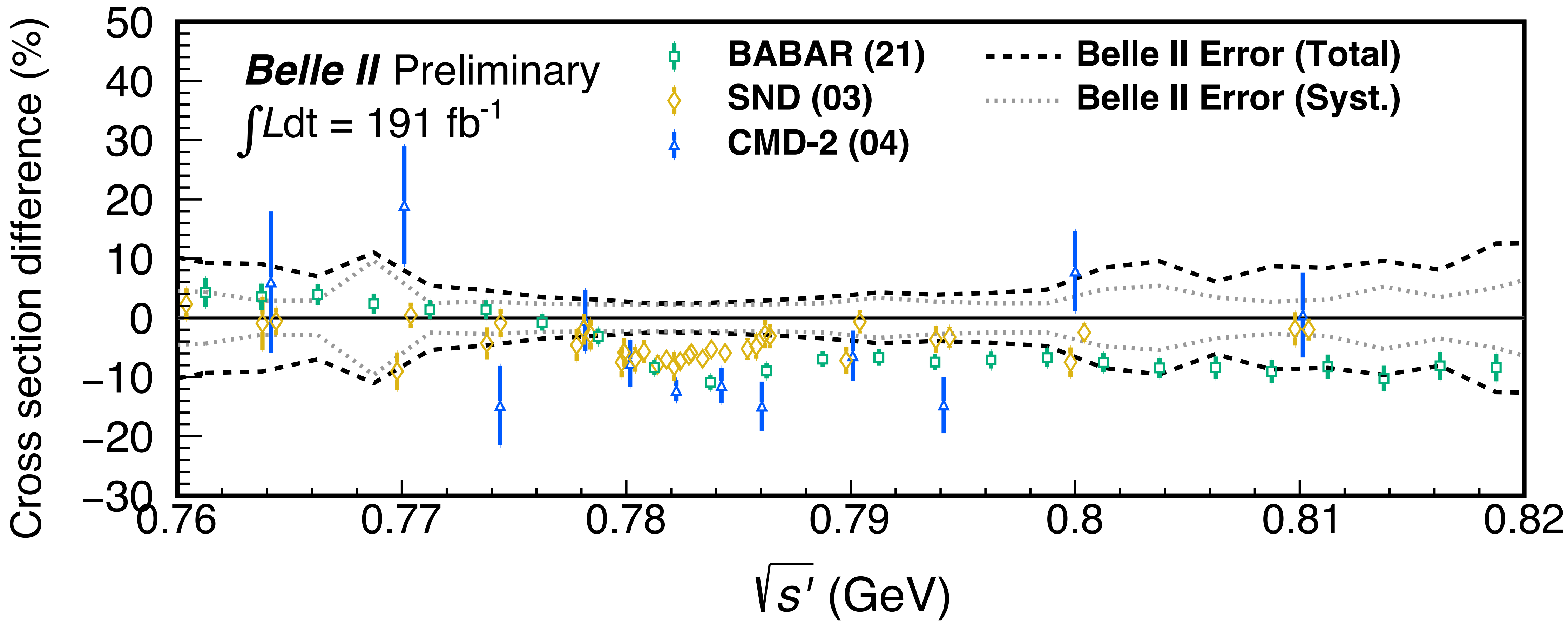
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ Results





- $a_\mu^{3\pi}(0.62 - 1.8\ \text{GeV}) = (48.91 \pm 0.23 \pm 1.07) \times 10^{-10}$
- main syst. uncertainties from efficiency and absence of NNLO in the MC
- 6.5% higher (2.5σ significant) than the global fit ➔ move to smaller 'anomaly'

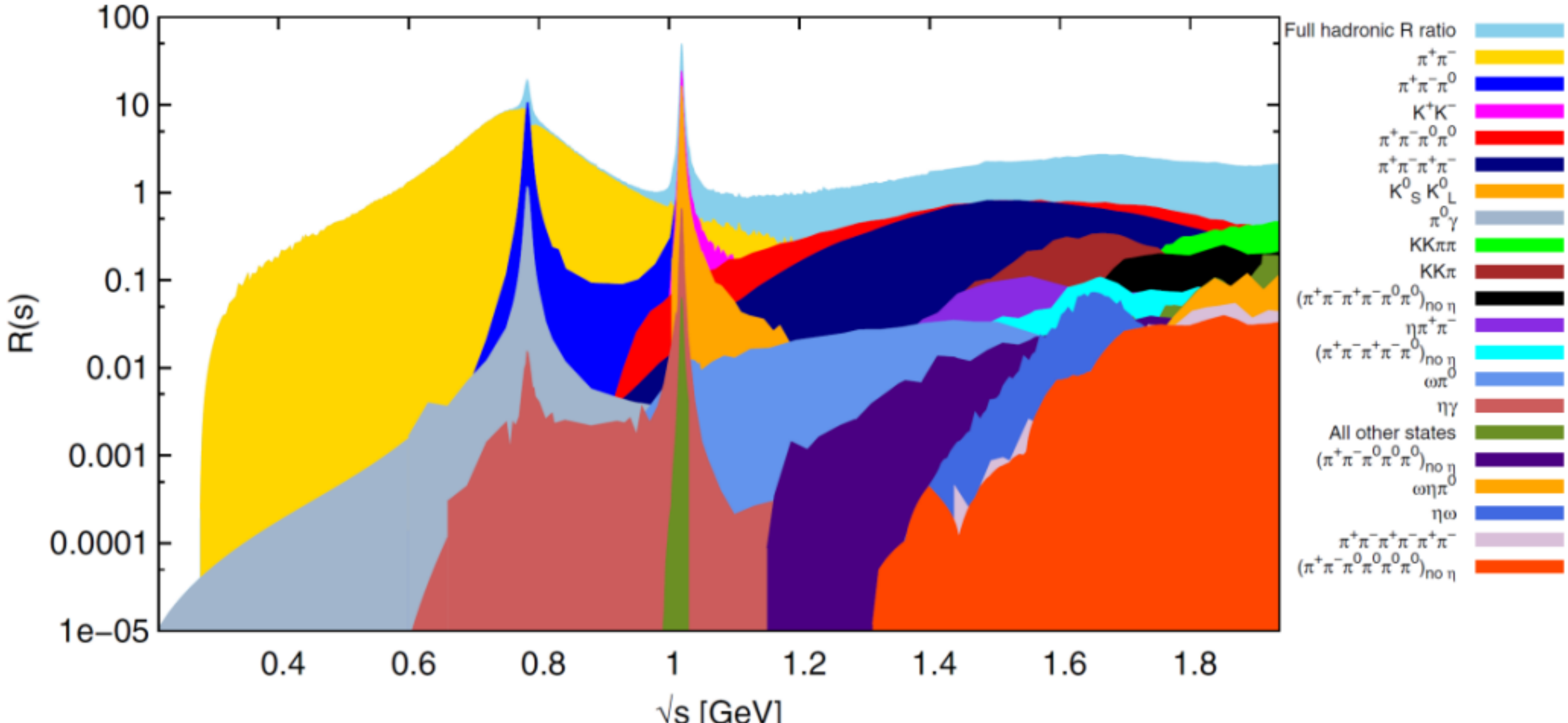
$$a_\mu^{3\pi}(0.62\text{–}1.8\,\text{GeV}) = (45.91 \pm 0.37 \pm 0.38) \times 10^{-10}.$$

Closing remarks

- Belle II has returned from LS1, and started Run 2 data taking in Feb. this year, collecting more than $0.5\ \mathrm{ab}^{-1}$ data sample in total.
- Belle II has searched for LFV and BNV decays of τ, and they are nearly background-free. We expect much improved results with more data to be pouring in.
- We also show recent searches for LFV processes, $\tau^- \to \ell^- V^0$ and $\Upsilon(2S) \to \ell^\pm \tau^\mp$ from Belle.
- In addition, we present Belle II measurement of $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$, which is highly relevant for muon (g-2).
- Run 2 is about to resume (in a few days) with the goal of collecting data sample of several ab^{-1} in the coming few years.

Thank you!

Measured R-ratio



(a) The hadronic R-ratio.